RUDIMENTARY

MAGNETISM:

BEING

A CONCISE EXPOSITION OF

THE

GENERAL PRINCIPLES OF MAGNETICAL SCIENCE

AND

THE PURPOSES TO WHICH IT HAS BEEN APPLIED.

With Fifty-six Illustrations.

PART III.

BY

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PREFACE.

It has been the author's endeavour to carry out in this supplementary or second volume of Rudimentary Magnetism the design specified in the Preface to Parts I. and II.; that is to say, an extension of elementary principles to an important class of natural magnetic phenomena, intimately connected with the physical universe, and with the prosperity and advancement of civilized life. Keeping in view the professed rudimentary character of the series of publications of which these volumes constitute a part, the author has thought that no kind of auxiliary information calculated to assist the student to a clear comprehension of the matter immediately before him should be considered as out of place in this work, however elementary and simple its character; so that the necessity of consulting other works, which may not always be at hand, may be as far as possible avoided. This, it is presumed, will be admitted as a sufficient ground for having in some instances referred to explanatory notes, which by the more advanced reader may be considered superfluous.

W. Snow Harris.

Plymouth, February, 1852.

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Page 119, line 7 from the top, *for* "sign of the angle," *read* "angle."
" 133, " 4, under E. *for* S.E. by S. *read* S.E. by E.
" " " 3, under S. *for* W.S.W. *read* S.S.W.
" " " 4, under S. *for* S.W. by W. *read* S.W. by S.

RUDIMENTARY MAGNETISM.

VI.

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173. THE wonderful influence of Magnetism as a physical agent would necessarily lead to an investigation of the laws by which its operations are regulated. The first and most obvious step in such an inquiry would be the general law of change in the effective force of Magnetism, as the distance at which it acts is varied, or, in other words, to find according to what law two magnetic particles attract or repel each other magnetically, as the distance between them is increased or decreased.

But, before entering upon this question, it may not be unimportant to the student to review briefly the numerical and mathematical elements essential to the progress of such an investigation.

174. We have first to observe,—That when any two quantities are so linked together that one of them cannot be changed in any degree without some relative change taking place in the other, then the one quantity is said to vary in some particular ratio of the other, either *directly* or *inversely*.

Suppose, for example, the power of a magnet to *increase*, when that peculiar condition of its molecules, which we term magnetic, becomes *exalted*, or reciprocally to *decrease* when that condition becomes *depressed*, then the force is said to vary in some proportion of the magnetic intensity *directly*. In this case, the two quantities both increase or decrease together. Again, the magnetic condition being the same, suppose the attractive force to *increase*, when the distance of its action is *diminished*, or to *decrease* when that distance is *increased*. In this case, the force is said to vary in some proportion of the distance; inversely, since one of the quantities increases as the other decreases; or conversely, one decreases as the other increases. We may, however, as is evident, have a great variety of different relative proportions, according to which such changes may ensue. It might be, for example, that when we doubled the exaltation of the magnetic condition, the force of the magnet would be also doubled, or it might be quadrupled, or increased in any other direct proportion, in which case the force would be said to vary, as the first, second, third, &c., powers of the magnetic intensity, as the case may be; and this also applies to the several inverse ratios as it respects the force, and distance of its action.*

* Not to leave anything connected with these inquiries unexplained, we venture to remark:—

That the successive multiplication of any given number by itself constitutes what have been termed powers of that number. Take, for example, the number 4, and multiply it by 4; then we have, adopting the common arithmetical signs $4 \times 4 = 16$. We have here two factors, producing 16; hence 16 is said to be the second power of 4, usually called the square of 4.

In like manner, again multiplying by 4, we have $16 \times 4 = 64$, which, being the same as $4 \times 4 \times 4$, gives three factors; hence 64 is termed the third power of 4, commonly called the cube of 4, and so on.

Such powers are represented by a small figure, called an index, placed at the head of the given number; thus, we may write successive powers of 4 thus—

$$4^2,\ 4^3,\ 4^4,\ 4^5,\ 4^6,\ \&c.;$$

175. Taking the inverse or reciprocal proportions, as being in the present inquiry well adapted to further explanatory illustration, we have to observe,—First. That when the force decreases in precisely the same inverse proportion as the distances increase, or reciprocally; that is to say, if at *half* the distance the force be *twice* as great, at *one-third* the distance *three times* as great, and so on; then the force is said to vary in the inverse simple ratio, or first power, of the distance, since we take the simple numbers, 1, 2, 3, &c. to represent the increase of the force. Supposing, however, that

thereby showing that 4 is multiplied into itself 2, 3, 4, &c. times. We may observe here, that in taking the indexes in the reverse direction, 6, 5, 4, 3, 2, &c., we should fall back upon 1, and even upon zero or 0, and hence arrive at 4^1 and at 4^0, that is, 4 raised to the first power, and 4 raised to the power of nothing; so that 4 taken as a single factor may be considered as the first power of 4. With respect to 4^0, or any other number whatever, raised to the power of 0, its value is always unity or 1, as is seen in any of the ordinary works on Algebra. Taking a to represent any number whatever, we have hence the following series:—

$$a^0,\ a^1,\ a^2,\ a^3,\ a^4,\ \&c.$$

When we again revert to the number, from which any given power has been obtained, we are said to extract the 2nd, 3rd, 4th, &c., root, as the case may be. Thus, the third root of 64 would be 4, since, as just remarked, $4 \times 4 \times 4 = 4^3 = 64$, so likewise, the second root of 16 would be 4, since we have $4 \times 4 = 4^2 = 16$; the second root has been called the square root, the third root the cube root.

In like manner, we have the 5th root of $32 = 2$, since $2 \times 2 \times 2 \times 2 \times 2 = 2^5 = 32$.

These roots are often represented by a fractional index, that is, by dividing the index of the power by the index of the root we wish to extract. Thus the square or 2nd root of 3 to the first power may be expressed thus, $3^{\frac{1}{2}}$; the cube or 3rd root of 5, by $5^{\frac{1}{3}}$, the square root of the 5th power of 2 by $2^{\frac{5}{2}}$, and so on. In this sense we are said to raise the given number to the power of $\frac{1}{2}$ or $\frac{1}{3}$, or $\frac{5}{2}$, as the case may be.

Commonly, such roots are represented by the index of the given root, placed within the sign $\sqrt{\ }$, thus, for the cube root of 3, we write $\sqrt[3]{3}$, for the 5th root of 2 $\sqrt[5]{2}$. In thus representing the square root of any given number, the small figure for the index is commonly omitted; thus, for square root of 9, we write simply $\sqrt{9}$.

at *one-half* the distance the force becomes *four times* as great, at *one-third* the distance *nine times* as great, and so on. In this case the force would be said to vary in the inverse duplicate ratio, or second power of the distance, since, to represent numerically the increase of the force, we must multiply the numbers 1, 2, 3, &c., into themselves, taking their second powers or squares. In a similar way, cases may arise in which the increase or decrease of the force is such as to require the third power or cubes of the numbers 1, 2, 3, 4, &c., to complete the proportion. This would arise when, at half the distance, the force had increased 8 times, at $\frac{1}{3}$ the distance, 27 times, and so on. In this case the law of the force is said to be as the cubes of the distances inversely, or in the inverse triplicate ratio of the distances; and thus we may continue for any other powers of the numbers 1, 2, 3, &c., so as to express laws of force in the inverse ratio of the 4th, 5th, 6th, or any other powers of the distance, did such forces exist.

A similar reasoning applies to forces increasing or decreasing in any inverse proportion *less* than that of the mere distance, as in the case of a force becoming doubled at $\frac{1}{4}$ the distance; trebled at $\frac{1}{9}$ the distance. In this case the force would be said to vary inversely as the square roots of the distance, since we must take the square roots of the numbers, 1, 4, 9, &c., to fulfil the proportion. In this way we express the law of force for any other roots of the distances, such as the cube, or 3rd root, the 4th root, &c.; and since these roots are mathematically denoted by fractional indexes, we may consider such forces as being in the inverse ratio of the $\frac{1}{2}$, $\frac{1}{3}$, $\frac{1}{4}$, &c., powers of the distances.

176. We may further extend this inquiry to cases of roots of the simple or other powers, such, for example, as the square root of the cube of the distance, being, as expressed mathematically, the cube of the distance raised to the power of $\frac{1}{2}$. An inverse proportion of this kind has been termed "sesquiplicate," and would apply to a case in which, by

decreasing the distance to $\frac{1}{2}$, $\frac{1}{3}$, &c., the force becomes about 3 times and 5 times as great, or very nearly. In like manner we may obtain forces varying in the inverse ratio of the square roots of the 5th powers of the distances, termed, "sesquiduplicate," and which applies to a case in which, by reducing the distance to $\frac{1}{2}$, $\frac{1}{3}$, $\frac{1}{4}$, &c., the force becomes increased between 5 and 6 times, and between 15 and 16 times, and 32 times respectively. In this way almost any observed experimental results, demonstrative of any particular law of force, may be mathematically represented.

177. The particular inverse ratio comprised in a series of experimental numerical results of this kind may be easily discovered by a slight inspection, since the forces multiplied by the simple or some other power of the corresponding distances should, in each particular case, give the same product. Thus, if at distance 12 the force were 8; at distance one-half or 6 the force became 16, we have in this case $12 \times 8 = 6 \times 16 = 96$, a simple inverse proportion; but if at distance 12 the force were 8, and at distance 6 the force became 32, then to obtain a coincident product, we must take the second powers or squares of the numbers 12 and 6, and we should then have $12^2 \times 8 = 6^2 \times 32$, or $144 \times 8 = 36 \times 32 = 1152$. In the case of direct proportion the products are differently circumstanced.*

178. We have been desirous to place this question (173)

* A complete apprehension of these practical researches and proportions being essential, the following numerical examples may not be altogether uncalled for :—

Let the distances be taken in some unit of measure, say tenths of an inch, and the corresponding forces in any other unit of measure, say degrees of an arc, as in the way described, Parts I. and II. sec. 128, and represented, Fig. 71, Frontispiece.

Suppose as a first example, we had obtained the following results :—

At distances..........	12·	6·	4
The forces are	5	10	15

Here we have the inverse simple proportions,—5 : 10 :: 6 : 12, and 5 : 15 :: 4 : 12, and 10 : 15 :: 4 : 6. Product of distances and forces = 60.

before the student in a simple and intelligible form, principally on account of the great importance of such inquiries

As a second example, let the results be—

At distances..........	12·	6·	4
Forces	2·	8	18

Here we have an inverse duplicate ratio, or square of the distance, furnishing the proportions—

$2 : 8 :: 6^2 : 12^2$, and $2 : 18 :: 4^2 : 12^2$, and $8 : 18 :: 4^2 : 6^2$;
that is $2 : 8 :: 36 : 144$, and $2 : 18 :: 16 : 144$, and $8 : 18 :: 16 : 36$.

Product of forces by squares of the distances, 288.

As a third example, suppose the experimental numbers were—

At distances..........	16	and	4
Forces are	2	,,	128

This would furnish a proportion inversely as the cube of the distance, and we should have—

$2 : 128 :: 4^3 : 16^3$; that is $2 : 128 :: 64 : 4096$.

Product of forces by cubes of the distance, 8192;

and so on for other changes of distance, or any other powers.

Let now the results be—

At distances..........	16	and	4
Forces	3	,,	6

In this case we should have a proportion in the inverse ratio of the square roots of the distances, and we should obtain the inverse proportion—

$3 : 6 :: 4^{\frac{1}{2}} : 16^{\frac{1}{2}}$; that is $3 : 6 :: \sqrt{4} : \sqrt{16}$, or $3 : 6 :: 2 : 4$;

Product of forces by square root of the distances $= 12$.

Again, let distances and forces be thus—

At distances..........	27	and	8
Forces	6	,,	4

Here we have the inverse proportion of the third or cube roots of the distances, and we obtain—

$6 : 4 :: 27^{\frac{1}{3}} : 8^{\frac{1}{3}}$; that is $6 : 4 :: \sqrt[3]{27} : \sqrt[3]{8}$, or $6 : 4 :: 3 : 2$.

Product of forces by third roots of distances $= 12$.

And so on for any other roots.

The following are examples of sesquiplicate and sesquiduplicate inverse proportions, being fractional powers or roots of powers.

Suppose that—

For distances	12	6	4
Forces were	5	14·2	26

to the general progress of science and theoretical knowledge. Thus Newton demonstrates, in his great work, "The Principia," that if the particles of common matter act on each other with a force varying in the inverse proportion of the

Here the forces are in inverse proportion to the square roots of the cubes of the distances, or in inverse sesquiplicate proportion, and we obtain such a proportion as this, for distances 12 and 6.

$$5 : 14{\cdot}2 :: 6^{\frac{3}{2}} : 12^{\frac{3}{2}}; \text{ that is } 5 : 14{\cdot}2 :: \sqrt{6^3} : \sqrt{12^3}, \text{ or}$$
$$5 : 14{\cdot}2 :: \sqrt{216} : \sqrt{1728}, \text{ or } 5 : 14{\cdot}2 :: 14{\cdot}7 : 41{\cdot}5 \text{ nearly.}$$

Product of forces by square roots of cubes of distances = 208 nearly.

A similar proportion is evident for the remaining forces and distances. As a last example—

Let distances be..........	12	6	3
And forces..............	4	22·5	128

Here the forces are in an inverse sesquiduplicate proportion, or in an inverse proportion to the square roots of the 5th power of the distances, and we obtain for distances 12 and 6 the following:—

$$4 : 22{\cdot}5 :: 6^{\frac{5}{2}} : 12^{\frac{5}{2}}, \text{ or } 4 : 22{\cdot}5 :: \sqrt{6^5} : \sqrt{12^5}; \text{ that is}$$
$$4 : 22{\cdot}5 :: \sqrt{7776} : \sqrt{248832}, \text{ or } 4 : 22{\cdot}5 :: 88{\cdot}5 : 499 \text{ nearly.}$$

Product of forces by square roots of 5th powers of distances = 1996 nearly.

The numerical operations in these examples have been taken as the numbers stand, without regard to any further reduction; but, as will be evident on examination, the arithmetical processes may be made smaller by taking the ratio of the distances and forces, instead of the distances and forces as given by experiment, when that can be done conveniently.

In cases of direct proportions the products are obtained by a method the reverse of this. We then multiply the terms crosswise, as it were. Suppose, for example, in three experiments, in which the magnetic intensity varied, we had obtained the following:—

Magnetic intensity	1	2	3
Force	4	8	12

In this case of direct proportion the magnetic intensity is not multiplied into its corresponding force, but into the force of the intensity with which it is compared. Thus, comparing intensity 1 with intensity 3, we have $1 \times 12 = 4 \times 3 = 12$; or, comparing intensity 2 with intensity 3, we have $2 \times 12 = 8 \times 3 = 24$, passing on crosswise of the table. In fact, we have here $1 : 3 :: 4 : 12$, or $3 \times 4 = 1 \times 12$; also $2 : 3 :: 8 : 12$, or $3 \times 8 = 2 \times 12$; and this applies to direct ratios involving powers or roots, as before.

squares of their distances, then the sensible action of hollow or solid spheres on each other will be the same as if all the matter of which they consist were collected in their centres, and that a particle placed anywhere within them would be in equilibrio, and not tend to move in any one direction; which he shows could not be the case under any other law of force. So, likewise, if the hidden source of electrical and magnetic phenomena be, as many suppose, a subtile elastic fluid of a specific kind, then, as was observed by the Honourable Henry Cavendish, in some of his manuscripts, such a fluid would be similar to air, if the repulsive force between the particles were inversely as any power of the distance greater than 3, only that the elasticity would be inversely as the $n+2$ power of their distances, or as the $\frac{n+2}{3}$ power of the density of the fluid; n being any number exceeding 3. But if n be equal to or less than 3, such an elastic fluid would be very different from that of air. Again, the times in which the planets revolve about the sun are in a sesquiplicate ratio of their distances from the centre, and not in a duplicate ratio. Hence, observes Cheyne, they "cannot be carried about by an harmonically circulating fluid," as was supposed by some of the ancient philosophers.

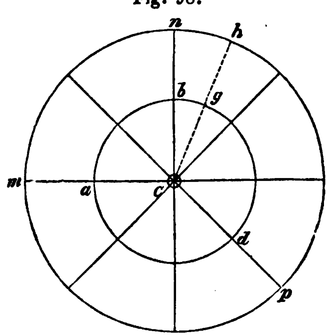
We may further remark in respect of Magnetism, that the force by which a magnetic needle is drawn towards its meridian when deflected from it (21), or towards a magnet, increases as the sine of the angle of the obliquity of action directly. Hence, as observed by Professor Robison, we cannot pretend to explain the action of a magnet by the impulsion of a stream of fluid, or by pressure arising from the motion of such a stream; for in this case the pressure on the needle must have diminished directly, as the square of the sine of the angle, at which the magnetic force operates on the needle. For example, the force at a right angle, or 90 degrees, should be 4 times greater than the force at an angle

of 30 degrees, whereas it is found to be only twice as great; being simply as the sines of the angles. It is, therefore, by the determination of the laws of such forces that we are enabled to advance our knowledge of the powers of nature.

179. Beside these preliminary explanations (173), there remain still to be considered one or two additional points equally essential to an intelligible and plain view of the questions involved in such inquiries, and the real sense in which we are to accept such expressions of the law of variation of certain forces as we have just cited (173).

To suppose any effect to be as the square or cube of its cause, either directly or inversely, is to suppose the effect to proceed partly from the cause and partly from nothing. For there is no axiom in Physics more evident than that which assigns between cause and effect a simple relation; any expression, therefore, which represents a force as being in any inverse ratio of a power of the distance greater than unity, may at first appear to involve an absurdity. We may hence infer that, when by experiment we have arrived at such a conclusion, the result is either a mixed result, compounded of two or more conjoined actions, or it is a result resolvable into some elementary condition of a simple kind, depending on the peculiar kind of agency upon which the exhibition of force depends. Take, for example, the following case of a central force, or emanation of any kind, extending its power in all directions into space, and hence becoming weaker in proportion to the surface of the spaces over which we may suppose it to expand. Let c (Fig. 98) represent such a central action; suppose, for example, a central source of light considered as luminous matter by way of illustra-

Fig. 98.



tion. Let *a b d*, *m n p*, be two great concentric circles, representing two concave hemispherical shells, whose centre *c* is the point of illumination, and whose radii *c a* and *c m* are to each other as 1 : 2; or, in other words, that point *n* is twice as far from the centre *c* as the point *b*. If in this case we take any two homologous segments, *b g*, *n h*, of these shells, it is clear that the segment *n h* will have four times the area of the interior similar segment *b g*; because the superficial areas of such shells will be in proportion to the squares of the diameters of their great circles *m n p*, and *a b d*, and these are supposed in this case to be as 1 : 2; so that the quantity of luminous matter (supposing light to be a material agency) which has emanated from the centre *c*, and fallen upon these shells, will in the outer shell *n* become distributed over 4 times the space, it would occupy, on the interior shell *b*; that is to say, in any one point, there will be only ¼ the quantity of light: hence the illumination of the arc *n h* will only be ¼ of the illumination of the arc *b g*; that is to say, the illumination will be directly, as the quantity of light in a given space, a simple relation of cause and effect. When, however, we refer this effect to the distance from the centre *c*, we perceive that the distances being as 2 : 1, the illumination of the whole of each shell is as 1 : 4. And thus light as a physical agency has been said to vary in intensity in the inverse ratio of the squares of the distance from the centre, in the way just explained (174); but the fact is, that the illumination of an equal area in each shell is directly as the quantity of the agency producing it.*

180. Again, in the cases of such powers as those of Magnetism and Electricity, we have to consider many conjoint

* The term intensity is really inapplicable here: it is a term, in science, only distinctive of quality, or of different states or degrees of power of the same agent; as when we say the heat of a red-hot iron is more intense than the heat of boiling water, or that moonlight is less intense than the light of the sun. Taking a particle of light from the same source, we have no reason for supposing it in a different state of intensity at different distances from the centre of illumination. If such

actions (33, 37). A magnet and common iron only operate on each other through the medium of a reciprocal induction (35); (38) when we change the distance of their action, we change at the same time the original condition or quantity of force in operation; so that we may conceive the total force of attraction to depend on the force induced in the iron (33) conjoined with the reciprocal induction on the magnet (37); and it may be here remarked, that in the apparent anxiety of philosophers to bring such forces indiscriminatively under the common law of gravity, and other central forces, they have probably encouraged a rather hasty generalization. All the forces in nature are not necessarily central forces, they may arise out of peculiar conditions of common matter, of which we have as yet but an indistinct notion, and be exerted between given points in determinate directions only, as appears to be indicated in Fig. 17, p. 24, Parts I. and II.; we have yet to learn, therefore, whether the force of Magnetism comes under the general conditions of ordinary central forces or not.

181. Newton, in his learned and profound work, "The Principia," considers magnetic force as being very different from that of gravity:—"The magnetic attraction is not (he says), as the matter attracted; some bodies are attracted more by the magnet, others less; most bodies not at all. The power of magnetism in one and the same body may be increased and diminished, and is sometimes far stronger for the quantity of matter than the power of gravity; and, in receding from the magnet, decreases not in the duplicate, but almost in the triplicate proportion of the distance, as nearly as I could judge from some rude observations."—*Book* iii., *Prop.* 6.

In the 23rd proposition of the Second Book, sec. 5, Newton imagines that, in magnetical bodies, "the attractive

were the case, both the quantity of light in a given space, and its intensity also, would change with the distance, and the illumination would then decrease much faster than that of the inverse squares of the distances.

virtue is terminated nearly in bodies of their own kind that are next them." "The virtue of the magnet," he says, "is contracted by the interposition of an iron plate, and is almost terminated at it, for bodies further off are not so much attracted by the magnet as by the iron plate." The experiments we have adduced (38), Fig. 29, have immediate reference to this observation.

182. Of the early experiments instituted with a view of determining the laws of magnetic forces, we have to notice first those of Hawksbee, printed in the Transactions of the Royal Society for the year 1712, vol. 27. A short needle, one inch in length, being poised on a fine point, fixed in the centre of a graduated quadrant, a natural magnet was placed, with one of its poles within certain measured distances of the centre of the needle, and the corresponding deviations of the needle from the meridian, noted in a way similar to that described, Parts I. and II., page 121, sec. 134, Fig. 82. The results have not generally been considered very satisfactory or regular; it is, nevertheless, worthy of remark, that, taking the tangents of the angles of deviation, corresponding to distances, which may be considered as very great in respect of the length of the needle, on the principles already laid down (134), then Hawksbee's results will be found consistent with each other, and, according to a law of force, varying in the inverse sesquiduplicate ratio (176) of the distances, as shown in the following analysis of the results:—

Distance in inches ..	12	18	24	30	36	42	48	54	60
Angles of deviation ..	69	43-30	24	13-30	8-45	5-30	3-50	3	2-30
Tangents of deviation .	2·6	·948	·445	·240	·153	·096	·067	·052	·043

Taking these tangents as representing the forces, they will be found all very nearly in the inverse proportion of the square roots of the 5th powers of the distances, in some cases precisely.*

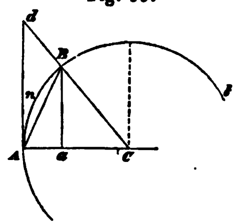
* In such experiments as these, we must recollect, that angles do not enter into ordinary calculation, except through the medium of certain lines taken to represent them. These lines have been termed sines,

183. Dr. Brook Taylor, in following up this method of experiment, was led at first to infer, "That the power of

tangents, secants, &c. It may not be out of place to recall briefly to the student's attention the nature of the two lines with which we are here especially concerned; viz., the tangent and sine of an angle.

Every angle A C B, Fig. 99, is measured by an arc A n B of a circle A B t, contained between its sides, and described from its point or vertex C as a centre. The line A B joining the extremities of the arc being called the chord of the arc.

Fig. 99.



Now a perpendicular line B a, drawn from the extremity B of the radius C B, forming one of the sides of the angle, directly upon the other side C A, has been termed the *sine of the angle* A C B; the length of this line, as is evident, will be greater or less as the angle A C B is greater or less.

Again, the line A *d* drawn perpendicular to the radius or side C A, upon the extremity A, and meeting the side C B, continued on to meet A *d* in the point *d*, has been termed the tangent of the angle A C B. This line also will increase and decrease with the magnitude of the angle.

If the radius C A be taken as unity, and be supposed to be divided into any number of parts, say 1000, or 10·000, or 100·000, then these lines, as applying to a given angle, will be found to contain a certain number of these parts. Thus, if we call radius A C = 1, or unity, and divided, say into 100 parts, then if the angle A C B be 30°, the sine B *a* will be one-half the radius A C, will contain 50 of these parts, and will be represented by ·5; the tangent A *d* will, in this case, contain about 57 parts, and will be represented by ·57. Now it is these numbers, as calculated and arranged in tables, with which we have to do, and not immediately with the angles themselves.

As all these lines, and the principles of their construction and use, are to be found in our elementary mathematical works, we will not longer dwell on them here. (*See* "Rudimentary Plane Trigonometry," p. 8.)

Comparing distances 12 and 24, which are as 1 : 2, we have

$$2{\cdot}6 : {\cdot}445 :: 2^{\frac{1}{2}} : 1 :: 5{\cdot}65 : 1, \text{ or } 5{\cdot}65 \times {\cdot}445 = 2{\cdot}6, \text{ or } 2{\cdot}5 = 2{\cdot}6 \text{ nearly.}$$

Take again distances 12 and 18, which are as 2 : 3, here we have

$$2{\cdot}6 : {\cdot}948 :: 3^{\frac{1}{2}} : 2^{\frac{1}{2}} :: 15{\cdot}5 : 5{\cdot}65, \text{ or } 5{\cdot}65 \times 2{\cdot}6 = 15{\cdot}5 \times {\cdot}948;$$
$$= 14{\cdot}6 \text{ nearly.}$$

In a similar way, the products for distances 30 and 60 are ·240 = ·246;

magnetism does not alter according to any particular law of the distances, but decreases much faster in the greater distances than in the near ones."* By subsequent and similar experiments, however, instituted by Whiston, Brook Taylor, and Hawksbee, conjointly, "the attractive power of the loadstone was found in the inverse sesquiduplicate ratio of the distances" (176). In these experiments they measured the forces by the sines of half the arcs of deviation, to which they endeavour to show the "force is always proportional."

184. About this period, experimental philosophy began to make considerable advances in Holland, and to excite very general interest; we consequently find the Dutch philosophers contributing largely to our knowledge of this branch of physics. The celebrated Muschenbroek instituted some experiments in 1724, the object of which was to find experimentally the law of magnetic attraction by the method of weights (125). Having suspended a spherical magnet from one arm of a balance, and poised it by weights suspended from the opposite arm, he placed a similar magnet immediately under it, and then proceeded to find the additional weights requisite to balance the attractive force at given distances between the opposed poles. These distances were regulated by raising or depressing the beam of the balance by means of a line passing over a pulley, and by which it was supported. The numerical results of the experiments were considered so unsatisfactory, as to lead to the conclusion that "no assignable proportion" exists between the forces and the distances, whether of attraction or repulsion, and "that magnets are indeed very surprising bodies, of which we know but little."†

for distances 12 and 36 we have 2·4 = 2·6, which may in each case be considered as sufficiently near.

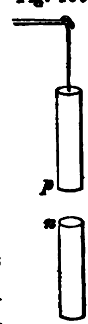
The greatest inequality appears to be for distances 18 and 54, being ·948 = ·814; all the others approach as nearly an inverse sesquiduplicate ratio as can be expected from the nature of the experiment.

* Phil. Trans. for 1721. † *Ibid.* for 1725.

185. In the "Introduction to Natural Philosophy,"* however, by Muschenbroek, we find the subject more satisfactorily investigated and pursued, the results being such as to demand very especial attention. The method of experiment did not materially differ from the former. The following cases comprise the amount of the investigation:—

First case.—Attractive force between a magnetic and iron cylinder. In this experiment a cylindrical magnet, *p*, Fig. 100, two inches in length, and about ·95 of an inch in diameter, was suspended over an equal cylinder of soft iron, *n*, and the attraction at different distances, *p n*, noted. The results were as follow:—

Fig. 100.

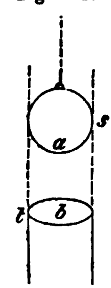


Distance in tenths of an inch	6	4	3	2	1	0
Force in grains	3	5	6	9	18	57

Muschenbroek observes, on this experiment, that the attractive forces are inversely as the intercepted cylindrical spaces, *p n*, that is, inversely as the distances (174), the law is uniform up to contact, or nearly so.

Second case.—Attraction between a spherical magnet and a magnetic cylinder. In this experiment a spherical magnet, *s*, Fig. 101, was suspended, with its north pole, *a*, downward, and a cylindrical magnet, *t*, of the same diameter, viz., ·95 of an inch, placed with its south pole, *b*, upward, immediately under it, the poles being in one straight line. The following were the results:—

Fig. 101.



Distance in tenths....	6	4	3	2	1	0
Force in grains	21	34	44	64	100	260

We may conceive, says Muschenbroek, "The sphere (*s*) to be in a hollow cylinder (*t s*), and let down at various distances (*a b*) from the cylindrical magnet. Then, considering the intercepted spaces (*t s*), the attractions will be found in the inverse sesquiplicate ratio of these

* Translated by Colson, in 1744, for the use of the Universities.

spaces, that is, inversely as the square root of the cubes of the spaces" (176). In referring the distances, however, to the near point, *a*, of the sphere, still the law does not very materially differ from the former case, being approximately in the inverse simple ratio of the distance, *a b*.

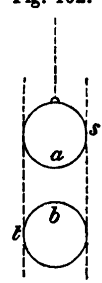
Third case.—Attraction between a magnetic sphere and a cylinder of iron of the same diameter = ·95 of an inch. In this experiment, a cylinder of iron, *b*, Fig. 101, was placed under the north pole, *a*, of the spherical magnet, *s*, this cylinder being the same as used in the first case. The following were the results:—

Distance in tenths	6	4	3	2	1	0
Force in grains	7	15	25	45	92	340

Muschenbroek, in referring the forces to the intercepted spaces (*t s*) as before, deduces the same law as in the former case; if, however, we refer the forces to the distance, *a b*, we find no regular law. The first three forces are inversely as the squares of the distances, or very nearly; the forces corresponding to distances 4 and 2 are in the inverse sesquiplicate ratio of the distances; this is also evident at distances 6 and 1. At the smaller distances, 2 and 1, the force is inversely as the simple distance, very nearly. At distances 6 and 2 no law is apparent.

Fourth case.—Attraction between a magnetic and iron sphere of equal diameters. In this experiment, a globe of iron, *b*, Fig. 102, was placed immediately under the north pole, *a*, of the suspended spherical magnet, *s*. The forces and distances in this case stood thus:—

Fig. 102.



Distance in tenths ..	8	6	4	3	2	1	0
Force in grains......	1	3·5	9	16	30	64	290

It is remarked by Muschenbroek, in this case, that if "we suppose both the spheres to have been included in a hollow cylinder (*t s*), and to be removed from one another at various distances, and the

intercepted hollow spaces (*t s*) to be considered; then we find the law in a reciprocal biquadratical ratio of the intercepted spaces; that is, inversely, as the 4th powers of the intercepted spaces (174). If, however, we refer the forces to the nearest points of distances, *a b*, we have all sorts of inverse proportions for the law of the force; thus, the forces at distances 8 and 4 are inversely as the 3rd power, or cubes of the distances, or very nearly; at distances 8 and 1 they are, inversely, as the second power or square of the distance; and this law holds approximatively for the forces at distances 6 and 4, for 6 and 3, for 6 and 2, and 4 and 3, in which last case it is exact.

At distances 8 and 2 the forces are as the square roots of the fifth powers of the distances inversely (176). Taking the near distances, 2 and 1, we have the forces nearly in the simple inverse ratio of the distances; whilst, at the distances 6 and 1, as also 4 and 2, the law approaches the inverse sesquiplicate ratio of the distance, that is, the square root of the cubes of the distances (176).

186. These results are not only curious, but they are really calculated, when properly considered, to throw very considerable light on the nature and mode of operation of magnetic force, as we shall presently see; and it is to be greatly regretted, that more attention has not been commonly bestowed on them. Muschenbroek's researches are usually quoted without due precision, and without any adequate explanation of the author's own peculiar deductions; they have been also not unfrequently treated lightly as furnishing no solid information whatever, from assumed imperfections in the nature of the experiments themselves.

187. We may infer, by the second and third cases, in which the force at contact, between a cylindrical and a spherical magnet, and the force between a similar cylinder of iron and the same spherical magnet is given, that when actually touching, a magnet does not attract another magnet so forcibly as it attracts simple iron, the force being,

in the one instance 260 grains, in the other 340 grains. The force, however, between the two magnets, diminishes less rapidly as the distance is increased, and would hence begin from a more remote point.

188. In the "Essai de Physique," printed at Leyden, in 1751, Muschenbroek more expressly refers to his early experiments in 1724, and although they led to no general conclusions, yet they furnish most important examples of the operation of magnetic forces under the given conditions. The following table, for example, contains the results of a series of observations on the force of two spherical magnets of very unequal diameters, opposed to each other at dissimilar poles, as in Fig. 102, one of the magnets being 6·5 inches in diameter, the other 1·5 inches.

Distance in lines—																
54	50	45	28	21	12	10	9	8	7	6	5	4	3	2	1	0
Force in grains—																
1·75	2·25	2·75	9	12	26	31	34	36	39	44	48	59	68	89	132	310

Many of these forces approach the inverse sesquiplicate ratio of the distances. It is, however, observed by Muschenbroek, that, from the unequal diameters of the spheres, "it is not easy to calculate the intercepted spaces: this led me to try the forces between a spherical magnet and a ball of iron, each ·95 of an inch in diameter." The attractions, as thus obtained, have been already given. Fourth Case (185).

The following are the results of observations on the repulsive poles of two magnets, and of two pieces of magnetic iron.

REPULSIVE FORCE OF TWO MAGNETS.

I.

Distance in lines	48	27	12	11	10	9	8
Force in grains	6·5	13	30	32	32	33	34

II.

Distance in lines	12	10	6	5	4	0
Force in grains	24	24	25·5	27·5	29	40

REPULSIVE FORCE OF MAGNETIC IRON.

III.

Distance in lines ..	12	10	6	5	4	3	2	1	0
Force in grains ..	3·5	4·25	7·5	7·75	8	10·5	14·5	14	Attn.

It is important to observe, in these last experiments, that, in the first forces and distances, the force is as the distances inversely, after which the increase of the repulsion decreases, and the force changes into attraction. We have thought it right to select these cases for consideration. For, notwithstanding that they led at first to the conclusion "that magnets are surprising bodies, of which we know but little," they will, nevertheless, be found to have a most important bearing on the question of magnetic force.

189. Martin, who followed Muschenbroek's method of experiment, found that for certain small distances the force of a magnetic pole, on a bar of soft iron, was in the inverse sesquiplicate ratio of the distance. In these experiments a plate of wood, of a thickness equal to the required distance, was interposed between the suspended magnet and iron. The magnetic pole being allowed to rest on the wood, and to which it would become drawn by the reciprocal attraction between the iron and magnet, small weights were then added to the scale-pan attached to the opposite arm of the balance, until the magnet pole became raised off the wood. The actual force and distances were as follows:—

Distance in inches............	$\frac{1}{4}$	$\frac{1}{2}$	$\frac{3}{4}$
Force in grains	156	58	28

It will be immediately perceived that these forces are inversely as the square roots of the cubes of the distances very nearly. Taking the distances as the numbers 1, 2, 3; we have $1 \times 156 = 2^{\frac{3}{2}} \times 58 = 3^{\frac{3}{2}} \times 28$ (177); the differences in the products, viz., 156, 164, and 145, are not so great as to place them without the limit of a fair approximation, especially when we take into account the difficulty of such experiments. If at distance $\frac{1}{2}$ the result had been 56 grains instead of 58, and at distance $\frac{3}{4}$ it had been 30 grains instead of 28, then the ratio would have been exact. The experiments appear to have been carefully made.*

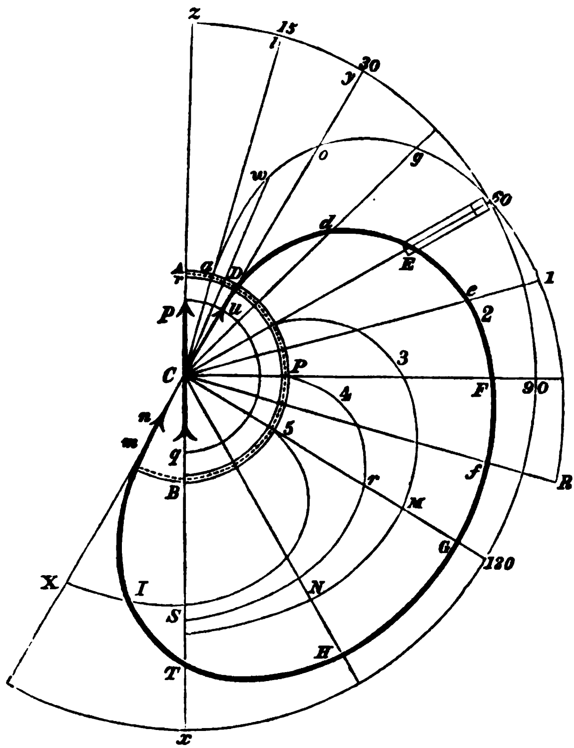
* "Philosophia Britannica," London, vol. i. p. 47.

190. Mayer, in an unpublished paper read before the Royal Society of Gottingen, in 1760, found the force of magnetic attraction to correspond with the general law of gravity. A deduction also arrived at by Michell, who says, in his capital treatise on Artificial Magnets, published in 1750, that in all the experiments of Hawksbee, Brook Taylor, and Muschenbroek, the force may really be in the inverse duplicate ratio of the distances, proper allowance being made for the disturbing changes in the magnetic forces (180) so inseparable from the nature of the experiment. He is hence led to conclude that the true law of the force is identical with that of gravity, although he does not set it down as certain. It is to be greatly regretted, as observed by Lambert, that the Royal Society of Gottingen did not publish Mayer's researches on this important physical question.

191. In the 22nd volume of "Histoire de l'Académie Royale des Sciences," Berlin, 1776, we find two beautiful memoirs on this subject by M. Lambert, which were considered by Dr. Robison as worthy of Newton himself. It is, therefore, imperative, in a treatise of this kind, to put the student in possession of the substance of these papers, more especially as a detailed and clear exposition of Lambert's experiments has seldom, if ever, appeared in our elementary works on this branch of science. In his first memoir the author endeavours to determine two very important laws of magnetic action; one relating to the change of force as depending upon the obliquity of its application, the other as referred to the distance. M. Lambert's course of experiment was as follows:—

A small needle, $p\ q$ (Fig. 103), about an inch in length, being poised on a fine centre C, fixed in a plane of wood, a circle A P B, one-half of which only is in the figure, was described about the needle, and divided into 180 degrees, both on the east and west side of the magnetic meridian x C z; the central or north point A of the semicircular arcs

Fig. 103.



being marked zero; the plane supporting the needle was made to turn about the centre C, so as to adjust the zero point A exactly in the line of the needle. This preparation made, Lambert placed a small magnet E, of a cubical figure, the same length and breadth as the needle, and one-half the thickness, in various positions, E, *e*, F, *f*, G, &c., about the needle, so as to deflect it from its meridian by a given angular quantity. We already know (134, 135) that in bringing a magnet near a compass needle in this way, the needle changes its position, so that by varying the position of the

magnet, we may produce any declination we please; we may also give the magnet E an infinity of different positions, or may change its place as from D, F, G, H, &c.; and hence may find such positions or points for its action as will all produce the same degree of declination in the needle. Now M. Lambert limited the precise position of the magnet in any particular point, E, to that in which the axis of the magnet and its south pole were directed to the centre C of the needle, as in the line E C; and he selected given declinations of the needle from 10 to 10 degrees on the west side of the meridian, and from 15, 30, 60, 90, up to 120 degrees on the east side. Having found all the points, as, for example, D *d*, E *e*, F *f*, G, H, I, &c., in which the magnet E, thus circumstanced, gave the same amount of declination, say 30 degrees, he proceeded to trace a curve, D E F G H I *m*, through all these points, and by means of which he endeavours to assign the law of force as directed to the centre C.

192. For the better tracing the various circles and curves, the plane on which this operation was performed was covered with fine paper. The figure is about ¼ of the size of the actual experiment, and as the curves on each side of the meridian *z* C *x* were found to be nearly similar, those on one side only are given, in order to avoid complication. In Fig. 103 then, C is the centre upon which the needle plays, *x* C *z* is the magnetic meridian. The angles A C *a*, A C D, A C E, A C F, A C G, are angles of 15, 30, 60, 90, 120 degrees, being the respective constant declinations producing the curves 1, 2, 3, 4, 5. Thus the magnet being in curve 2, the declination of needle was always 30 degrees. When in curve 3, it was always 60 degrees, and so on. By this arrangement an equilibrium is obtained between three forces: viz., the magnetic force of the needle; the directive force, or unknown power by which it is drawn to the meridian A B; and the force of the magnet E by which the needle is deflected or drawn from its meridian.

193. In comparing the curves thus obtained, Lambert only assumes, what in fact is shown by all experience, that the magnetic force decreases when the distance at which it operates increases. In estimating the element of distance, he finds it sufficient to take the distance between the extremity E of the magnet and the centre C of the needle. So that if it be merely required to know if the force of the magnet has been more or less great in one point than in another, as, for example, in points E and F, then the right lines C E, C F will be sufficient for that purpose, and the force of the magnet may be taken as being less as these lines are longer.

194. With a view to simplify our conceptions of M. Lambert's investigations, we will confine our references principally to one of the curves which he traced, viz., to the curve No. 2, corresponding to a deflection of 30 degrees, and which caused the needle, $p\,q$, to assume the direction n C u, making with the meridian, z C x, the angle z C y = 30 degrees. It may be here observed, that if we take, on either side of the radius, C G, any two points, F H, making equal angles, G C F, G C H, with that radius, and suppose the magnet to be in F, and attracting the north pole, p, of the needle with a force $= p$, and repelling the south pole, q, with a force $= q$, then we have only to place the magnet in H, and it will reciprocally employ force $= p$, to repel the south pole, and the force $= q$ to attract the north pole, that is to say, the distances G H and G F being equal, the position of the needle would not vary; and reciprocally, in order not to vary, these distances must be equal. The curve, D E F G H I m, therefore is similar to itself on each side of the right line C G, so that C G is an axis or diameter of that curve, and divides it into two similar and equal parts, that is, supposing a perfect resemblance and equality of force in both poles of the magnet. Mr. Lambert calls this axis, C G, a transverse axis or diameter, because it passes through the centre at right angles to the deflected position of the needle. Thus, when the

magnet E is in the curve E G H, just mentioned, the deflection being 30°, the position of the needle is the line *m* C D, and the axis is C G, and so for any other curve; thus, when the deflection is 60°, and the needle is in the line C E, then the axis of the curve is C N, being always at right angles to the direction of the needle. We may further observe, that all the curves extend themselves from the centre up to the points by which their respective diameters pass, as at X S N G R.

195. These experimental conditions of Lambert's investigations being understood, we may proceed to his analysis of them; and first, as relates to the change of force liable to occur from a greater or less degree of obliquity in the action of magnetism on the needle, considered as a lever, a most important element in the progress of such inquiries. Assuming, as we have just shown (194), that it requires everywhere the same effective force to retain the needle at the same declination, we might conclude conversely, that for the same degree of declination the distance should be always the same; but such is evidently not the case, since the points D E F G, &c., in curve No. 2, are all at different distances from the centre C, hence all the force of the magnet E cannot be everywhere exerted; some compensation between the force and distance must hence arise, if the needle at different distances is to remain in the same position. Now, we may observe that in different points of a given curve, D E F G H, the action of the magnet E is more or less oblique upon the needle *p q*; thus, the needle being retained in the line *n u*, at a deflection of 30°, the angle of obliquity at point E is E C D, at point F it is F C D, at point H it is H C D; that is to say, the obliquity of the action increases with the distances. In order, therefore, that the needle should remain stationary, the decrease of the force due to the increase of distance should be exactly the same as decrease of power arising from the increased obliquity of the action. To determine the law of the change of

force from obliquity, Lambert calls to his aid the polar or magnetic force by which the needle is drawn toward the meridian, and which also acts obliquely upon the needle, whenever we deflect it from its meridian. Thus the needle, p q, being drawn from its meridian into the line n u, the oblique action of the polar force is the angle z C y. To distinguish in certain cases the oblique action of the magnet E from this last obliquity, he calls the angles of obliquity of the magnet E angles of incidence. Thus, angles E C D, F C D, &c., are angles of incidence as regards the obliquity of magnetism in the action of the magnet E on the needle. If the law of the variation of the force as regards a change of distance were really known, we could easily determine the law of the increase or decrease of force as depending upon obliquity of action; for the effect depending on this obliquity of incidence would be in the same curve in an inverse ratio of the force, in order that the compound resulting effect might retain the needle in the same position; but Lambert had not determined this law, and is hence led to another method by taking into consideration the action of the polar force on the needle.

196. To determine the effect of obliquity, considered as depending upon the angle of obliquity, that is, as being some function* of that angle, Lambert took two equal distances, C d and C r, in which the absolute force of the magnet, independent of obliquity, might be considered the same. We may here observe, that when the magnet is in point d, the needle is found in direction C u, being, by the experi-

* This term *function* is in very common and accepted use in physico-mathematical science. It is employed to express, either algebraically or otherwise, any quantity whose value depends upon that of another. Thus the extent of the circumference of a circle will depend on the length of the radius of the circle. The circumference is hence said to be a function of the radius. In the present case the effective force of the magnetic power will depend upon the angle of incidence. It is hence said to be a function of that angle; so that we have to find what is the actual value or relation of this function to the magnetic power.

ment for that point, deflected 30°. The angle of incidence $d\ \text{C}\ u$ is therefore 15°, and the obliquity of the polar force is the angle $z\ \text{C}\ y=30°$. Again, the magnet being in r, the needle is in direction C F, being by the experiment for curve 4, deflected 90°. In this point, then, angle of incidence of magnet is F C G$=30°$, and angle of obliquity of polar force z C F$=90°$. Let now the whole magnetic polar force$=$M, and the whole force of magnet$=m$, then, because the needle is at rest, either the whole or some part of the magnetic polar force must be in equilibrio with the whole or some part of the force of the magnet; and as these forces will depend upon the angle of obliquity, we have for points d and r, calling the function we require$=f$, the following equations:—

$\text{M} \times f\,30° = m \times f\,15°$, and $\text{M} : m :: f\,15° : f\,30°$ for point d,

$\text{M} \times f\,90° = m \times f\,30°$, and $\text{M} : m :: f\,30° : f\,90°$ for point r.*

But between these four functions, in the proportions thus deduced, we obtain $f\,15° : f\,30° :: f\,30° : f\,90°$.

Now this proportion leads at once to the value or nature of the function required$=f$, since in the ordinary trigonometrical calculations and tables we find that the sines of these angles fulfil the conditions of this proportion. In fact, we have sin $14\frac{1}{2}$: sin 30° :: sin 30° : sin 90°, that is,

* The student will easily see, that to represent the equilibrium of the forces in operation, we must multiply the total magnetic force by the function of the angle of obliquity at which the force acts, and upon which the modification of the whole force depends. Thus, suppose that when the obliquity of action was a given quantity, that only $\frac{1}{8}$th part of the total force, for example, was effective in retaining the needle at a given deflection, we should, in this case, express it by $\frac{1}{8}$ of M, calling generally the magnetism M; that is to say, we should multiply M by $\frac{1}{8}$. But since we do not know what portion of the total forces are in operation, we are content to represent it by some function of the angle of obliquity; and, therefore, in the above, write $\text{M} \times f\,30°$, or $m \times f\,15°$, as the case may be. It is further evident that, in the equilibrium of these forces, we have in all cases some portion of the total polar force acting at a constant distance in equilibrio, with some portion of the total force of the magnet acting at variable distances from the needle; hence we write, in the cases quoted,

$$\text{M} \times f\,30° = m \times f\,15° \text{ and } \text{M} \times f\,90° = m \times f\,30°.$$

$\cdot 250 : \cdot 5 :: \cdot 5 : 1$,* which is sufficiently near for our purpose, and leaves little or no doubt as to the nature of f.

197. From this investigation, then, we may conclude that the action of magnetism on a magnetic needle, considered as a lever, is proportionate to the sine of the angle of obliquity of its direction; and that hence the effective force which operates in restoring the needle to its meridian, when drawn aside from it, is directly as the sine of the angle of its deflection—an important deduction. "If," says Robison, "M. Lambert's discoveries had terminated here, it must be granted that he had made a notable discovery in Magnetism."

This important result was fully established by a variety of other experiments. Thus taking other points, f and g, equally distant from centre C, or very nearly so, we have the angles of incidence g C $a = 30°$, and f C D $= 75°$; the needle for curve 1 being deflected 15° in direction C a; and for curve 2 being 30° in direction C D. The obliquities of the respective polar forces are consequently z C $t = 15°$, and z C $y = 30°$.

From whence we obtain for points g and f the two following proportions:—

$$m \times f^{n}\, 30° = \text{M} \times f^{n}\, 15°, \text{ which gives } m : \text{M} :: f^{n}\, 15° : f^{n}\, 30°;$$

and

$$m \times f^{n}\, 75° = \text{M} \times f^{n}\, 30°, \text{ which gives } m : \text{M} :: f^{n}\, 30° : f^{n}\, 75°.$$

From these four functions we have, by the ordinary rules,

$$f^{n}\, 15° : f_{n}\, 30° :: f^{n}\, 30° : f_{n}\, 75°;$$

that is, sin 15°: sin 30°:: sin 30°: sin 75 (196);

or, $\cdot 2589 : \cdot 5 :: \cdot 5 : \cdot 966$.

And $\cdot 2589 \times \cdot 966 = \cdot 5 \times \cdot 5$, or $\cdot 250 = \cdot 258$, which is a sufficiently close approximation.

198. Having thus determined the first, and apparently the most simple law of Magnetism, Lambert proceeds to apply it in his further investigations of the law of force as regards distance. With this view, let the total polar force, which draws the needle to its meridian, be considered as unity or 1, and suppose that the magnet E being in some

* See (182) note.

point of the curve D E G, the needle is deflected 30°, and is in the direction C D. In this case the sine of 30° being ·5, the effective polar force becomes represented by $1 \times ·5$ (196, note); that is to say, it may be expressed by ·5. Now the needle being stationary, in whatever point of curve 2 the magnet be placed, it is clear that the oblique or effective force of the magnet in any point, *d*, E, *e*, must be equal also ·5; because in these points it exactly balances the polar force.

Now, let the actual or inherent force of the magnet at any distance, C E, C G, &c.$=m$, and call the angle of incidence or obliquity of its action $=\phi$, then we have the effective force in every point of the curve $=m \times \sin\phi$; but as this force, as just shown, must be $=·5$, we have therefore by these two values

$$m \times \sin\phi = ·5 \text{ and } m = \frac{·5}{\sin\phi}.$$

Taking now the different angles of incidence, *d* C D, E C D, *e* C D, &c., for the successive points *d* E, *e*, &c., and which are by construction, 15, 30, 45, 60, &c., up to 120° (192), and dividing ·5 by the sines of these angles, we obtain the value of *m*, or absolute force of the magnet, in each point of the curve at a measurable distance from the centre C; consequently, in laying off the respective distances C D, C *d*, C E, &c., upon a given scale, we have the respective values of the force and distance represented by numbers. M. Lambert estimates the distance in terms of a unit of measure $=\frac{1}{4}$ the length of the needle. The forces and distances thus determined will be as in the following table :*—

Points of curve ..	*d*	E	*e*	F	*f*	G
Distances$=d$	2·71	3·62	4·17	4·33	4·48	4·61
Forces$=f$	1·93	1·00	0·7	0·57	0·51	0·5

199. It will be observed, that in comparing these distances

* This way of noting the results of the experiment is not the same as that adopted by M. Lambert, who gives several distinct and elaborate tables, which, in a rudimentary work of this kind, could not well be introduced. It became requisite, therefore, to simplify them, and bring the results under a less complicated form. No alteration, however, has been made in the course followed by the author, or in his numbers, which are given as found in his table.

and forces as before (182), there is a general approximation to the law of the inverse square of the distance, more especially in the points F, f, G, in which the products of the forces, multiplied by the squares of the respective distances (177), are 10·6, 10·2, 10·6; the nearer points, however, as d E e, give the products 13·87, 13·10, 12·1, which exhibit greater differences. M. Lambert, however, goes on to observe,—that the distances here given are taken between the extremity of the magnet E, and centre, C, of the needle, —that these may not be the true distances of the magnetic action,—still he prefers letting the numbers remain as they are in the table, and subject them to such calculation as may be found requisite, merely bearing in mind, that whatever be the true distances, they must be in some inverse ratio of the forces.

200. Supposing Magnetism to be a species of central force, analogous with the force of gravity (179), it would then come under the same general law as regards the distance of its action, and would be in the inverse duplicate ratio of the distance (175). Assuming this to be the case, we may obtain the true distances corresponding to the forces by means of the general expression for this law. Thus, let $f =$ the effective force of the magnet in points d E, e F, &c., and let the true distance of action we require to find $= \Delta$, then we have

$$f \propto \frac{1}{\Delta^2}, \text{ and, consequently, } \Delta \propto \frac{1}{\sqrt{f}}$$

If, therefore, we extract the roots of the numbers in the preceding table, represented by f, we shall, in carrying out the operation indicated in the above formula, obtain a series of numbers which, although not equal to the true distances, will still vary in the same direct ratio, and which may become equal to the true distances if multiplied by some constant $=$ C, so that, in representing these numbers by δ we should have $\Delta = \delta \times$ C.*

* The student must remember, that although a given quantity may

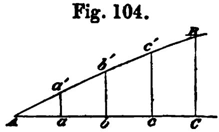
Subjecting, then, the forces f to the indicated operation $\frac{1}{\sqrt{f}}$, we obtain, for the respective points d, E, e, F, &c., the following proportionate distances :—

Points	d	E	e	F	f	G
Proportionate distances $=\delta$ ..	0·719	1·00	1·189	1·316	1·39	1·414

M. Lambert deduces for the mean value of the constant, by which these numbers must be multiplied, $C = 2{\cdot}2$, as given from the whole series of experiments in the successive curves 1, 2, 3, 4, 5 (Fig. 103). The true distance, therefore, will be represented by $\Delta = \delta \times 2{\cdot}2$; so that by comparing the product of the above numbers by 2·2 with the measured distances $= d$, as given in the preceding table, we immediately arrive at the required correction, if any.* Take, for example,

change in the same proportion as another and greater quantity, yet we cannot ever consider the two quantities as equal. To complete the equality it becomes requisite to multiply the lesser quantity by some constant number. Take, for example, the right-angled triangle A C B, and suppose it divided by parallels $a\,a'$, $b\,b'$, $c\,c'$, &c. ; and in such way, for example, that distance A a from the vertex A is twice the length of the parallel $a\,a'$. Then we have A b double of $b\,b'$, and A c double of $c'\,c$, and so on ; and $a\,a'$, $b\,b'$, $d\,d'$, &c., will increase in exactly the same proportion as A a, A b, A c, &c. ; so that if A $b = 2$ A a, then $b\,b' = 2\,a\,a'$, and so on. Still $a\,a'$, $b\,b'$, &c., can never be taken equal to A a, A b, &c. We may, however, in this case make them equal by multiplying $a\,a'$, $b\,b'$, &c., by 2, which is the constant quantity here required, but which constant in the above formula we require to determine.

Fig. 104.



* To get the value of C, let the difference between the true and observed distance $= x$, then we have $d \pm x = \delta \times C$. Take now any two values of d, say in points E and G, as given in the former table, then we have

$$3{\cdot}62 \pm x = 1 \times C \text{ for point E,}$$

$$\text{and } 4{\cdot}62 \pm x = 1{\cdot}414 \times C \text{ for point G.}$$

Subtracting equation of point E from equation for point G, we have

$$1{\cdot}01 = {\cdot}414 \times C \text{ and } C = \frac{1{\cdot}01}{{\cdot}414} = 2{\cdot}4 \text{ nearly.}$$

the numbers in the preceding table at points d and G, then we have for Δ, that is, the true distance,

$$0{\cdot}719 \times 2{\cdot}2 = 1{\cdot}58 \text{ for point } d,$$

$$\text{and } 1{\cdot}414 \times 2{\cdot}2 = 3{\cdot}11 \text{ for point G.}$$

But the measured distances for these points $= d$, as given in the former table are $d = 2{\cdot}71$ for point d,

$$\text{and } d = 4{\cdot}61 \text{ for point G.}$$

The respective errors, therefore, or

$$d - \Delta \text{ are } 2{\cdot}71 - 1{\cdot}58 = 1{\cdot}13 \text{ for point } d,$$

$$\text{and } 4{\cdot}61 - 3{\cdot}11 = 1{\cdot}5 \text{ for point G.}$$

The mean of these, or $\frac{1{\cdot}13 + 1{\cdot}5}{2} = 1{\cdot}31$ nearly, which turns out to be the mean value of x upon the whole series of experiments in the different curves, that is the quantity to be subtracted from the measured distances in order to obtain the true distances, upon the hypothesis that the force is as the squares of the distances inversely, as in the case of gravity. These numbers x and C being determined, we have $d - 1{\cdot}31 = \delta \times 2{\cdot}2$, and hence $d = \delta \times 2{\cdot}2 + 1{\cdot}31$, which is the formula deduced by M. Lambert for determining d by calculation, and comparing the result with d as given in the first table.

In extending this formula through the numbers for the series of curves 1, 2, 3, 4, 5, deduced as in the first table (198), M. Lambert finds the differences between the measured and calculated values of d comparatively small, and as often positive as negative; and hence concludes that the formula $d = \delta \times 2{\cdot}2 + 1{\cdot}31$ is, upon the whole, correct.

201. Admitting the truth of this formula, we arrive at a somewhat remarkable result: viz., that to obtain the distance, the square of which is in a reciprocal inverse ratio of the force of the magnet, we must take, for the true distance,

Upon a mean of the whole series of experiments for all the curves, 1, 2, 3, 4, 5, Mr. Lambert finds the mean value of $C = 2{\cdot}2$, or, as he expresses it, $\frac{11}{5}$.

the distance been the centre of the needle and the extremity of the magnet, minus the quantity 1·31, which is greater than half the length of the needle.* So that what may be called the centre of attraction of the magnet is found out of the magnet, and what may be called the centre of attraction of the needle is found out of the needle. So that the common centre of attraction may be conceived to be in the semicircular interval A p (Fig. 103) being as much nearer the needle p q, as its force is less than that of the magnet E. M. Lambert thinks that, in the case before us, it falls about the point r, at 1·31 distance from the centre of the needle C A, being the least radius or distance at which the magnet could be placed without altogether fixing the needle independently of the polar force.

Professor Robison appears to view this deduction as somewhat anomalous, and as arising out of the complicated nature of the experiment. Yet if the force be such as anticipated by Lambert, there does not appear any greater difficulty in conceiving such a result, than in conceiving the common centre of gravity of two bodies of unequal magnitudes to fall without the bodies. Thus the common centre of gravity of the earth and moon is neither within the earth or moon, but in some point intermediate between them; being as much nearer the earth as the mass of the earth is greater than that of the moon.

Under this impression, however, the professor was led to repeat Lambert's experiments with magnets, consisting of a slender steel rod, terminating in small balls, in which case he found the force to be nearly in the centre of each ball, and to vary in the inverse duplicate ratio of the distances with singular precision.

202. Such are the principal features of Lambert's first memoir on the important question of the law of magnetic force. In a following subsequent memoir "On the Curvature of the Magnetic Current," he continues his series of

* The unit of measure being made = half the length of the needle (198).

experiments, and examines with singular ingenuity, mathematical skill, and address, the action of the directive or polar force of a magnet upon a small needle. In the preceding experiments Lambert had always preserved the axis of the magnet in a right line passing through the centre of the needle. This condition, however, is not altogether requisite in every case. He therefore, in these subsequent researches, places the magnet more or less oblique to that line, but always preserving the same angle of obliquity for comparative experiments. The question whether such curves as those which are represented in Part I. (28), depend on a circulating fluid, Lambert considers of no moment. Still the curves exist, and the problem for determining the nature of such curves will still arise, the axis of a small needle freely suspended will, in various points, always be a tangent to these curves ; so that we may, without ambiguity of language, call them "curves of the magnetic current." If there be such a current, the term will be true to the letter ; if not, the algebraic nature of such curves will suffer no change. In order to determine the nature of these curves, as bearing on a large and important class of natural magnetic phenomena, Lambert endeavours to examine still further the general laws of Magnetism, and the position, size, figure, and force of the great magnet which he supposes to reside in the earth. The limits of this work will not permit us to enter fully upon this beautiful memoir, which, as remarked by Dr. Robison, would have done credit to Newton himself; more especially as it embraces other considerations than those immediately connected with our present subject. So far, however, as it bears on the elementary laws of Magnetism, Lambert concludes, "that the effect of each particle of the magnet on each particle of the needle, and reciprocally, is as the absolute force or magnetic intensity of the particles directly, and as the squares of the distances inversely."

203. About twenty years after Lambert's experiments, Coulombe turned the attention of his ingenious and compre-

hensive mind to this subject;* and by means of the torsion balance (132), and method of oscillation (138), not only confirmed the deductions of Lambert, but also added to our knowledge of magnetic force in a most extraordinary degree. Having placed a linear magnet, 24 inches in length, in the stirrup of his balance (132), he was enabled to measure the force required to maintain this needle at various angles from its natural direction, and thus, by a direct experiment, he confirmed the principle of Lambert (197), viz., that the force urging a magnetic needle toward the magnetic meridian when drawn aside from it, is proportional to the sine of the angle of its deflection. Referring to the explanations given (133), the following are the forces and angles in four different experiments, and by which it will be seen that the forces or degrees of torsion requisite to maintain the needle at the given angles, are sensibly proportional to the sines of these angles.

Micromatic circles	1	2	4	5·5
Degrees of torsion	349·5	698·75	1394	1895
Angles of Deflection ..	10°-30	21°-15	46°	85°
Sines of angles	·1822	·3624	·7193	·9961

204. To understand clearly these results, it will be necessary to recollect, that the reactive force exerted by the wire when subjected to twist, is exactly proportional to the degree of twist to which it has been subjected. This is the fundamental principle of the instrument (132).† This degree of twist or torsion may be either measured by actually twisting the wire itself at its upper extremity, Fig. 80 (132), against a resisting force beneath, or otherwise turning the wire from below against a fixed point above. In either case the torsion force is proportional to the angle of torsion. Now, in such experiments as those just quoted, in which a magnetic needle

* Memoir of the Royal Academy of Sciences, 1786 and 1787.

† We avail ourselves of this opportunity of correcting an error, seventh line from the top, p. 119, Parts I. and II., for "sine of the angle or arc," *read* angle or arc.

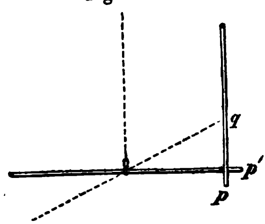
is forced from its directive position through a given angle, say 46°, by actually twisting the wire any number of degrees against the directive force of the needle, and by which it tends to the magnetic meridian, we must, to obtain the actual force of torsion, holding the needle at any given angle, subtract from the number of degrees which we have twisted the wire, the degrees representing the angle of deflection of needle; for, imagine that we had forcibly retained the needle in its original position, whilst we had twisted the wire 4 circles of the micrometer (Fig. 80, sec. 132), that is 4 times $360 = 1440°$, and that, on liberating the needle, it became deflected, and rested at 46°, then, as is evident, the total torsion of the wire would become relaxed by that quantity, and we should have for the absolute force of torsion, holding the needle at 46°, $1440 - 46 = 1394°$, as given in the table; and similarly for the other given angles.

205. Having determined this point, Coulombe proceeds to examine the law of the repulsive force of two similar magnetic poles, and in the following way :—

Two equally-tempered and magnetic steel wires, each 24 inches in length, and about the $\frac{1}{10}$ of an inch in diameter, were placed, one of them in the balance, and the value of its directive power or force dragging it to the meridian, at any given angle determined. This force, in terms of the torsion force, was, for this particular case, equal to 35°, for 1° of deflection of the needle; that is to say, in order to force the needle 1° from its meridian, it was requisite to turn the mecrometer, Fig. 80 (133) 35° of the circle.* This being ascertained, the other wire was placed vertically in the me-

* Coulombe found that 2 circles of torsion deflected the needle 20°, which gave a force of torsion for $20° = 720 - 20 = 700$. Now the directive force of the needle being as the sine of the angle of deflection, we may, from this experiment, obtain the force for any other angle m, since we have this proportion, 700 or force at 20° : f, the force at angle m :: sin 20 : sin m, or $f \times \sin 20 = 700 \times \sin m$, or $f = \frac{700 \times \sin m}{\sin 20}$. If we

Fig. 105.



ridian, with its inferior pole at right angles to the similar pole of the needle, as represented in the annexed Fig. 105, and in such way as to admit of the two wires being considered as intersecting each other at an inch within their similar polar extremities, p p'. As a necessary consequence (31), the pole p' of the horizontal needle, placed in the balance, becomes repelled, and turns away from the pole p of the fixed vertical needle, until arrested by the torsion of the wire, and a balance obtained to the repulsive force. In this case the needle was balanced at an angle of torsion of 24°. The next step was to determine what amount of torsion was requisite to balance the repulsive force at certain other angles or distances between the repelling poles, p p'. With this view the wire was twisted against the repulsive force by turning the micrometer 3 complete circles, or $3 \times 360° = 1080°$. The pole p' of the needle now stood within 17° of the vertical pole p. In like manner, 8 circles or $8 \times 360° = 2880°$, brought the repellant poles within 12° of each other. Let us pause here for a moment to consider what are the actual or total forces in operation at each of the arcs of distance, 24°, 17°, and 12°.

206. In the first place, we have to consider, that not only is the horizontal needle, p', pressed back toward the vertical needle, p, by the reactive force of the torsion, but it is likewise urged toward the vertical needle by its own directive power or tendency to the meridian; we must therefore add this assistant force in each case. This is effected by turning it into degrees of torsion, at the rate of 35° of torsion for

take the arcs themselves, instead of the sines, which we may do here without any great error, we have $\frac{f = 700\ m}{20} = 35\ m$. If we take $m = 1°$, then the force equals 35°, that is 35° of torsion, as observed.

each degree of angular deflection from the meridian, according to the preliminary experiment above given (204); for, since as a fundamental principle of the instrument, the torsion force goes on regularly increasing with the angular twist of the wire, it is sufficient to know the actual force for one degree, to get the force for any number of degrees In the first experiment, therefore, when the angular distance of the poles pp' was 24°, the total force in terms of torsion, balancing the repulsive force, must have been $24+(24\times35)=24+840=864$. For force at angular distance, 17°, we have to combine the new torsion $=3$ circles, with the torsion for 17°, and the directive force at 17°, so that we have $(3\times360)+17+(17\times35)=1080+17+595=1692$ for the total force at angle 17°. In like manner, we obtain the total force at $12°=8$ circles $+12+(12\times35)=2880+32+420=3312$; so that the distances and corresponding forces will stand thus:—

Distances	12	17	24
Forces	3312	1692	864

207. Now, these forces are in the inverse duplicate ratio of the distances, or very nearly. Thus, at distances 12 and 24, which are as 1:2, we have the inverse forces 864 and 3312, which are as 1:4; that is to say (174), we have the inverse proportion $3312:864::2^2:1$ or $4\times864=3312$, nearly, or $3456=3312$. Had the force at 24° been 868 instead of 864, the accordance would have been complete. Now the difference 36 between these numbers is not above one degree of error in the position of the needle, at the rate of 35° of torsion to 1° of angular deflection; the result, therefore, is perhaps as near as could be expected, for it is to be remembered that the action of the poles upon each other is a little oblique; the distances are really as the chords of the arcs, and not as the arcs themselves, beside that the experiment is not an experiment with two particles, but two portions of a magnetic wire. Admitting all this, however, it is still to

be observed, that the force at the near distance, 12, is not so great as it should be by calculation in the proportion of 3312 : 8456, taking the force at 24 as 864; we shall have occasion to refer to this fact as we proceed.

208. These experiments, by Lambert and Coulombe, were followed up, about the year 1817, by Professor Hanstein, of Christiana, who, in a valuable work entitled "Inquiries concerning the Magnetism of the Earth," deduces many important laws of ordinary magnetic forces.

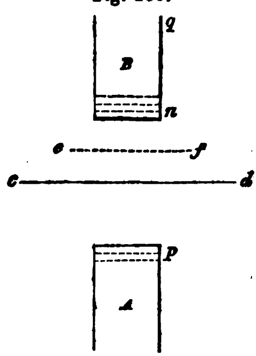
Although Professor Hanstein's method of experiment is virtually the same as that of Hawsksbee (182), yet the method of analysis is peculiarly his own. Hanstein's apparatus may be taken as identical with that described (134) Fig. 82, the straight line, E W, being divided into portions such that ten of them were equal to the half axis of the artificial magnet used in the experiment. Having assumed that the magnetic intensity of any particle in a magnet is proportionate to some power of the distance from the magnetic centre (26); and that the force between any two particles is in some inverse ratio of their mutual distance, a general expression is deduced, for the effect which a linear magnet would have upon a magnetic particle, situated anywhere in the line of the prolonged axis of the magnet. This determined, and the angles of deviation of the needle (Fig. 82), at different distances from the magnet M, accurately noted for each distance, the Professor proceeds to compare the results of calculation with those of the actual experiment, and shows that the supposition of the force being in an inverse power of the distance equal to 1 or 3, entirely disagrees with observation; whilst, on the other hand, if the power be made equal to 2, the numbers found by experiment differ but little from those found by calculation. The value of the power of the distance, representing the increase or decrease of intensity from the magnetic centre, does not appear to have so great an influence on the result. Hanstein, however, thinks that this power is also equal to 2, although, by taking it as

1 or 3, the differences from actual observation are not always considerable.

From these inquiries, Hanstein thinks he is entitled to conclude, "That the attractive or repulsive force with which two magnetic particles affect each other, is always as their intensities directly, and as the square of their mutual distance inversely," thus confirming the deductions of Lambert and Coulombe.

209. *Further Inquiries concerning the Nature and Laws of Magnetic Forces.*—Although our knowledge of magnetic force has been very greatly advanced by these several researches, it yet remains to be seen whether the law deduced be a general law, applicable to every case of magnetic action considered as a central force (179), or whether it be only a particular law of some peculiar agency operating between the surfaces of magnetic bodies in a way similar to that of electricity, which, as now well known, is confined to the limiting surfaces of opposed conductors.*

Fig. 106.



We have seen (33) that when a magnetic bar A, Fig. 106, is opposed to a similar, but smaller, bar of iron B, then a new polarity n is induced in the near parts n of the iron, opposite in kind to that of the opposed polarity A, whilst another polarity, q, arises in its more distant parts, similar in polarity to that of the polarity A, but opposite to that of the induced polarity n: this, however, is not all. On further examination, we find (37) that the temporary polarity n, thus induced in the near surface of the iron, operates in its turn on the near surface p of the magnet, producing there, by a species of reflection or rever-

* Rudimentary Electricity, (21), p. 17, and (98), p. 111, second edition.

beration, what may be considered as a new polarity *p*, opposite in kind to that of the induced polarity *n*, but similar to that of the permanent polarity A; that is to say, a portion of the force, which under the ordinary conditions of magnetized steel is directed towards the centre of the magnet (28), becomes now determined toward the iron in direction *p n*.

These changes induced in the magnetism of the two bodies, have been considered by some writers as casual and disturbing forces, superadded as it were to the primary magnetic action, which they imagine to be a distinct power, or emanation as it were from a centre, and operating in the way of other central forces (179). Michell had evidently adopted this view (190); as also Dr. Robison, who thinks that the phenomena of magnetic attraction and repulsion, as commonly observed, are not calculated to develop the real law of magnetic force: "For in the experiments made on attraction at different distances, the magnetism is continually increasing, and hence the attraction will appear to increase in a higher rate than the just one;" and that, hence, "the observed law must be different from the real law." * If we look, however, very narrowly into the nature of this kind of physical force, we shall immediately perceive that it is altogether an inductive process. Induction, as observed by Faraday, in respect of electricity,† is the essential function of all magnetic development. So far, therefore, from these induced actions being merely superadded or disturbing forces, they are the very essence of the force itself. It is in fact the mutual play of these inductive powers which constitutes magnetic action in all its variety of form; we recognize no other action in the observed phenomena of magnetic attractions and repulsions: and it is hence to the laws of these induced changes to which we must look for an intelligible development of what we have termed the general law of magnetic force.

* Mechanical Philosophy, vol. iv. pp. 217 and 273.

† Researches in Electricity, 1178.

210. It is here to be remembered that we know nothing of that peculiar condition of steel we term magnetic, except through the medium of its effects upon ferruginous bodies. We may, however, infer, as already explained (14), that in a magnetized bar two forces are developed, the tendency of which is to recombine and restore the condition of neutrality under which they previously existed. Taking, therefore, a magnetic bar apart from the influence of all other ferruginous matter, we may consider the action of these opposite forces as being directly upon or toward each other, either through the particles of the steel, or through surrounding space. The experiment we have adduced (28), Fig. 16, is highly illustrative of this kind of action: the ferruginous particles being evidently bent into curves, and apparently uniting the forces in points similarly placed, on each side of the magnetic centre. When, therefore, we present to one extremity *p*, Fig. 106, of a magnet A, a mass of iron B, capable of assuming the magnetic state, or otherwise, the opposite pole of another magnet, we divèrt, as it were, some portion of the force, resident in that extremity *p*, from its previous direction towards the centre of the bar A, and cause it to act in the direction of the opposed iron or other opposed polarity, as appears strongly indicated in Fig. 17 (28). And this it is which constitutes the reciprocal or reflected force *p*, Fig. 106, to which we have just adverted; and it is upon these two forces that the reciprocal force between the two bodies depends.

211. This species of reverberation of force between the opposed poles having once commenced, may still continue; that is to say, a secondary wave or reverberation may proceed from the new force *p*, which again reaching the iron, is again reflected back upon the magnetic pole, calling into activity a still further portion of the opposite force in the direction of the iron; each reverberation becoming weaker until the wave vanishes, as it were, into rest.

The late Mr. Murphy, of Caius College, Cambridge, ap-

plies, in his profound mathematical work on Electricity and Heat, a somewhat similar principle to the theory of electrical action, and which he terms, "Principle of Successive Influences." Professor W. Thomson also, of the Glasgow University, resorts to a view of this kind, conceiving that in the reciprocal force of attraction, as exerted between a charged and neutral body, certain images or reflections of power are produced within the opposed conductors, and which become perpetuated in a way similar to that of reflections between two mirrors.*

How, or in what way, the kind of influence to which we have just adverted (209) commences, or from whence it first proceeds, has never yet been fully explained. The first action may, for anything we know to the contrary, proceed from the influence of the iron on the magnet; the magnet being a body in a peculiar condition, which renders it sensible of impressions from ferruginous matter. Hence may arise that determination of a given portion of the polarity next the iron which we have just described (210), and upon which may depend a subsequent and similar determination of the opposite polarity resident in the iron toward the magnet, and a retiring, as it were, of the similar polarity in the reverse direction. In whatever way, however, these two inductions arise, they are evidently the immediate source of the reciprocal attraction as observed to arise between the opposed bodies: this appears in great measure evident in Fig. 17 (28). On the contrary, when these inductive actions do not arise, or if they be resisted by any existing magnetic condition, then not only is there an absence of all apparent force, as we perceive in presenting to the pole of a magnet any non-magnetic body (30), but a totally opposite force ensues; the bodies actually repulse each other; as also fully indicated in Fig. 18 (28). Moreover, it may be shown, that the attractive force between a magnetic pole and soft iron, is only in proportion to the induction of which the iron is

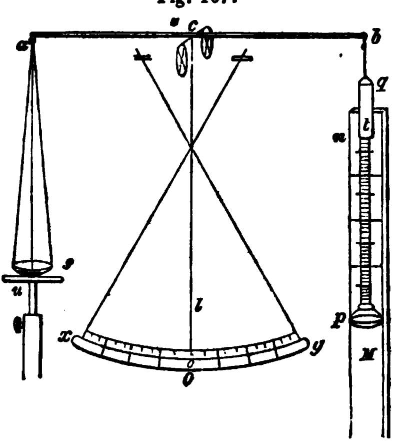
* Rudimentary Electricity, (101), p. 115, second edition.

susceptible, whatever the amount of permanent magnetic development in the steel.

Magnetic attractions and repulsions then, as commonly observed, being the result of a species of inductive reverberation (209) between opposed magnetic bodies, it follows: that in order to arrive at a correct view of this species of force, and determine the law of its action, we must necessarily commence with an investigation of the laws and operation of the elementary forces of induction.

212. The magnetometer already described (126), Fig. 76, and the simple balance-beam adverted to (37), Fig. 29, are well adapted to the measurement of these and other magnetic forces. The first has been very fully explained in all its details (126); the latter when applied to very refined purposes should be mounted on friction-rollers, such as shown Fig. 75 (126), and the whole of the framework, with its attached arc, be sustained on a central sliding column of support, the altitude of which can be varied by means of rack-work, as in the column of the magnetometer, Fig. 76, so as to change the distance readily between the small trial cylinder *t*, Fig. 107, or other body suspended from one of the arms, and any other magnetic substance M brought to act on it. The general arrangement is represented in the annexed figure, the framework and column of support being omitted, in order to avoid complication. In the instrument as here shown, the suspended

Fig. 107.



bodies play freely on two pins, run transversely at *a* and *b*, through slits cut in the extremities of the beam, which is 16 inches long. The scale-pan *s* is supported on a small circular plane, set on a sliding-piece *u*, so as to admit of adjustment. The arc *x o y* is the ⅛th part of a circle, and is divided into 100 parts on each side the centre *o*, which is marked zero; the radius of the arc is 16 inches, the index *l* is neatly formed of three or four pieces of reed straw, terminating in a fine bristle; it is attached to the balance at *c* by insertion on a brass pin projecting from a light brass band encircling the beam, and through which the axis passes. The forces corresponding to any given number of degrees of the arc, are determined experimentally by placing small weights, either in the scale-pan at *s*, or on the suspended iron *t*. The axis being a little above the centre of gravity of the beam, the balance does not immediately overset, but admits of a given inclination: the forces in this case will be very nearly as the small angles at which the beam inclines; so that the degrees of the arc measuring these angles will be nearly as the weights inclining the beam. Attractive forces are measured on the arc in direction *o x*, repulsive forces in the opposite direction *o y*.

This balance is only applicable to the measurement of very small forces, such as those exerted by magnets and iron at distances approaching the limit of action. In the application of it, we employ precisely the same kind of apparatus for sustaining the magnets and iron as that already described for the Hydrostatic Balance (126).

213. The direct and reciprocal forces of induction (209) are examined by these instruments according to the methods described (128, 129, 130). To determine the law of the direct induction (33), the magnet and iron are attached to a divided scale, Fig. 79, and then brought under the trial cylinder; so that in making the distance *a b* constant, and varying the distance N S, the rate of increase or decrease of the induction upon the near extremity S of the inter-

mediate iron, as measured by the distant and associated polarity at *b*, may be pretty fairly estimated; the reciprocal attraction between the trial cylinder *a*, and the induced pole *b*, will, as observed by Newton (181), entirely result from the intermediate iron; hence we may infer, all other things being the same, that the proximate induction at s will vary with the distant polarity at *b*. When the bodies are laid horizontally, as in the annexed Fig. 108, the trial cylinder *t* is immediately over the distant extremity of the iron, the force being taken through a short cylindrical armature *a*. Fig. 78 (129) is further illustrative of this experiment. To measure the reflected force (37), we first observe the degrees of attraction between the pole of a magnet and the trial cylinder *t*, either placed vertically, as in Fig. 107, or horizontally, as in the annexed Fig. 109. A mass of iron *m*, or the opposite pole of a permanent magnet, is then caused to approach the pole *p* of the magnet M, through certain measured distances as before: this will cause the index to decline (37). Now the degrees of declination may, within certain limits, be taken as a measure of the reciprocal force of the induced pole *n* upon the pole *p* of the magnet M, the distance of the trial cylinder *t* being constant, and the force allowed to operate through a short cylindrical armature of soft iron as before.

Fig. 108.

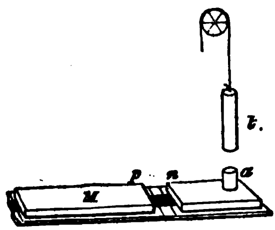
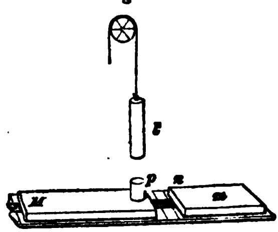


Fig. 109.



The forces of induction may in all these cases be considered as proportional to the square roots of the degrees of attraction, as given by the instrument, since by a law of

charge which has been fully established in similar electrical actions,* and which we shall further show as equally true for magnetic actions, the force is as the square of the quantity of magnetism in operation (229).

214. It appears by an extensive series of experiments conducted in this way, that a limit exists in respect of these elementary inductive forces, different for different magnets, and varying with the magnetic conditions of the experiment, toward which the increments in the force continually approach with greater or less rapidity, as the distance $p\,n$, Fig. 107, is diminished, as if the opposed bodies were only susceptible of a given amount of magnetic change.

Taking the force toward the limit of the action, the amount of induction is in some inverse ratio greater than that of the simple distance; it was not found, however, in any case which could be satisfactorily determined, to exceed the inverse sesquiplicate ratio, or $\frac{3}{2}$ power of the distance (176). As the distance becomes diminished, the induction approaches the inverse simple ratio of the distance (175), and varies commonly according to that law. At less distances, the induction begins to vary in some ratio less than that of the simple distance inversely, such, for example, as the $\frac{2}{3}$ power of the distance inversely (176). At small distances the induction was generally observed to be as the $\frac{1}{2}$ power or square roots of the distances inversely (175); thus causing corresponding changes in the general law of attraction reciprocally exerted between the opposed bodies.

When the convergence is slow, the law of the induced forces may be taken for a long series of terms as constant; but should any circumstance interfere to accelerate the convergence, such as a particular texture or condition of the magnetic steel or iron, or a high magnetic power, then the law of force may appear subject to irregularity. As a general result, however, we may conclude, that the elementary force

* Rudimentary Electricity, (102), p. 117, second edition.

of magnetic induction is as the magnetism directly, and from the $\frac{1}{2}$ to the $\frac{3}{2}$ power of the distance inversely.

215. This understood, let us see how far these results may be applied in explanation of the different laws of force experimentally deduced by the many eminent philosophers who have turned their attention to this important question.

Let A, Fig. 106 (209), represent a magnet opposed to a similar mass of iron B, at some given distance $p\ n$. Let the small space n be taken to represent the direct induction on the near extremity of the iron B, and the small space p, the reciprocal or reflected induction on the near pole of the magnet A; and suppose that every magnetic particle in n attracts every magnetic particle in p, and reciprocally. Moreover, let all the particles in $n = a$, and all the particles in $p = b$, and take distance $p\ n$ as a unit of distance, then total force at this distance $= 1$ will be represented by $a \times b = a\,b$. For the attraction of one particle of n to all the particles in p will be as b; the attraction of two particles of n to all the particles of p will be as $2\,b$; of three particles, as $3\,b$; of m particles, as $m\,b$; so that if b represent all the particles and $m = a$, the total force will be $= a\,b$.

Suppose, now, we decrease the distance. Let the distance, for example, be reduced to one half $p\ n$, the magnet A being brought up to the line $c\,d$, then supposing the induction to vary as the simple distance inversely (214), n will become $2\,n$, and p will become $2\,p$. In this case call the particles in $n = 2\,a$, and the particles in $p = 2\,b$; then, considering $2\,a$ and $2\,b$ as double particles, we have attraction of one double particle in n for all the double particles in p, as $2\,b$; of two double particles in n, for all the double particles in p, as $2 \times 2\,b = 4\,b$; of three double particles, as $3 \times 3\,b = 9\,b$; and so on to m particles, which will be as $m \times 2\,b = 2\,m\,b$. If $m = 2\,a$, the total force will be represented by $2\,a \times 2\,b = 4\,a\,b = 2^2 a\,b$.

Let distance $p\ n$ be now further reduced. Suppose it

reduced to $\frac{1}{3}$ p n, and that the magnet be now brought up the line $e f$. Then, according to the same law of inductic n becomes 3 n, and reflected force p becomes 3 p. Reasoni as before, we have total force $= 3\ a \times 3\ b = 9\ a\ b = 3^2\ a$ If distance be now diminished to $\frac{1}{4}$ p n, we have similar total force represented by $4\ a \times 4\ b = 16\ a\ b = 4^2\ a\ b$, a so on.

Taking, therefore, first force $a\ b$ as a unit of force, a distance $p\ n$ as a unit of distance, we have, at distances 1, $\frac{1}{3}$, $\frac{1}{4}$, &c., the corresponding forces 1, 2^2, 3^2, 4^2, &c.; that is say, the forces are in the inverse duplicate ratio of the di tances (175), according to the law of Lambert and Co lombe.

Exp. 53. This law may be verified experimentally b placing a magnet, Fig. 107 (212), immediately under th trial cylinder t, and taking the forces within a range of abou $\frac{1}{3}$ to $\frac{1}{8}$ of the sensible limit of action. Thus the forces an distances, as deduced by the hydrostatic magnetomete (126), were as follow; the distances being taken in tenth of an inch, the forces in degrees—

Distances	12	10	8	6	5
Forces	2	3	5	8·5	12

216. We will now take a case in which the induce forces, in approaching a limit (214), are no longer in th inverse ratio of the simple distances, but as the $\frac{1}{2}$ pow or square roots of the distances inversely. Then, takin a unit of force $= a\ b$, and a unit of distance $= p\ n$, a reasoning as before, suppose in decreasing the distance line $c\ d$, that is, to $\frac{1}{2}$ the former distance, induced force instead of becoming 2 n, is now only 1·4 n, or nearly, whil p, instead of becoming 2 p, is now only 1·4 p, that is, th square roots of the distances inversely. In this case, callin force at distance unity $= a\ b$, we have force at distan $\frac{1}{2} = 1{\cdot}4\ a \times 1{\cdot}4\ b = 2\ a\ b$ nearly. Similarly, in decreasin the distance to $\frac{1}{3}$ p n, n becomes 1·73 n, instead of 3 n, and becomes 1·73 p, instead of 3 p, and we have for total force

distance $\frac{1}{3} = 1 \cdot 73\, a \times 1 \cdot 73\, b = 3\, a\, b$, and so on. Thus, whilst the distances are 1, $\frac{1}{2}$, $\frac{1}{3}$, &c., the forces are 1, 2, 3. In this case the reciprocal forces of attraction are as the distances inversely (175), according to the law observed by Muschenbroek (185), cases 1 and 2; Œpinus, Tent. Theor. Electr. et Magn. 301, &c., also arrived at a similar result.

Exp. 54. This law may be fully verified by experiment as in the preceding case, by taking the force and distances within about one-third the sensible limit of action. Thus, with a given magnetic power, the distances being 4 and 2, the forces were 8 and 16. In comparing the distances and forces with magnets of low power, especially in cases of magnets by induction, the forces are generally as the distances inversely. Let, for example, the distance S N, Fig. 79 (130), be made constant, and distance $a\, b$ varied, the reciprocal forces of attraction, between a and b, will be almost invariably as the distances inversely.

217. Should the induced forces in any case vary in some other inverse ratio of the distance, suppose, for example, it should approach the $\frac{3}{2}$ power of the distance, which it may (214), then on diminishing distance to the line $c\, d$, Fig. 106, $= \frac{1}{2}$ distance $p\, n$; force n will become $1 \cdot 68\, n$ instead of $2\, n$, and force p will be $1 \cdot 68\, p$ instead of $2\, p$, and we should have the total force at distance $\frac{1}{2}$ expressed by $1 \cdot 68\, a \times 1 \cdot 68\, b = 2 \cdot 8\, a\, b$ nearly. Similarly at distance $\frac{1}{3}$ it would be $2 \cdot 8\, a \times 2 \cdot 8\, b = 7 \cdot 84\, a\, b$; since, according to the same law, n would become $2 \cdot 8\, n$, and p would become $2 \cdot 8\, p$, instead of $3\, n$ and $3\, p$ (215), and so on. In this case, whilst the distances are 1, $\frac{1}{2}$, $\frac{1}{3}$, the forces are 1, 2·8, 7·8; that is to say, they are in the inverse sesquiplicate ratio, or $\frac{3}{2}$ power of the distances, according to the law deduced by Martin in three very unexceptionable experiments (189): that is to say, at $\frac{1}{2}$ and $\frac{1}{3}$ the distance the forces become nearly 3 times and 5 times as great (176).

Exp. 55. This result may be verified, as in the preceding experiments, by noting the distances and forces within

about $\frac{1}{8}$ and $\frac{3}{8}$ of the sensible limit of action. Thus, at distances 8 and 4, the forces were 5 and 14, being in the inverse sesquiplicate ratio of the distance, or very nearly.

218. When the induced forces vary in any inverse ratio greater than that of the simple distance, we obtain laws of force in an inverse ratio greater than that of the second powers. Let, for example, the induced forces approach the $\frac{3}{2}$ powers of the distances inversely (214), so that on reducing distance $p\ n$ to $\frac{1}{2}$; n becomes $2 \cdot 83\ n$; at distance $\frac{1}{3}$ it becomes $5 \cdot 2\ n$, and so on; instead of $2\ n$ and $3\ n$ as in the first case. And let force p vary similarly, then we have force at distance $\frac{1}{2} = 2 \cdot 83\ a \times 2 \cdot 83\ b = 8\ a\ b = 2^3\ a\ b$; at distance $\frac{1}{3}$ it would be $5 \cdot 2\ a \times 5 \cdot 2\ b = 27\ a\ b = 3^3\ a\ b$, and so on: that is to say, taking $a\ b$ as a unit of force at a unit of distance $= p\ n$, as before, we have at distances 1, $\frac{1}{2}$, $\frac{1}{3}$, the corresponding forces, 1, 2^3, 3^3, &c., that is, 1, 8, 27; by which we perceive, that as the distances decrease, the forces increase in the proportion of the cubes of the distances inversely (175); being the law of force given by Sir Isaac Newton (181).

Exp. 56. We may verify this result experimentally, by taking the forces and distances from about $\frac{3}{8}$ to $\frac{5}{8}$ of the limit of action. The balanced beam, Fig. 107 (212), is well adapted to this experiment; and if we substitute a small magnet for the trial cylinder t, so as to extend the limit of action, then this law will become very apparent. Thus, at a distance of six inches, the force was observed to be 2°; at 3 inches it increased to 16°.

219. By taking the induced forces $p\ n$ in some other inverse ratio (214), we may in a similar way obtain a law of of force, such as found by Brook Taylor, Whiston, and Hawskbee. Suppose, for example, that at distance $\frac{1}{2}$, n becomes $2 \cdot 37$ times as great, and that p varies with it, we should then have the total force at distance $\frac{1}{2} = 2 \cdot 37\ a \times 2 \cdot 37\ b = 5 \cdot 6\ a\ b$ nearly, which would be as the square root of the fifth power of the distance inversely (176), and which result may frequently be obtained in taking the forces and

distances within limits from about the $\frac{2}{5}$ to $\frac{3}{5}$ of the sensible distance of action.

If magnetic forces could be satisfactorily traced to the limits of their vanishing points, we might probably obtain laws of force in the inverse ratio of the fourth or fifth powers of the distances; at least there appears no reason to suppose that the law of the inverse cube of the distance is the ultimate law of this species of force; supposing it to depend on the mutual play of the inductive actions we have described (209, 214).

220. It may be, perhaps, as well to remark here, that in all these laws of force as thus deduced, and which differ from that of the inverse square of the distance, the same result may be arrived at in supposing a limit to one only of the forces (209). If we suppose, for example, the reflected force p, Fig. 106, to change so little at small distances from the magnet, as to admit of being taken as constant. Then the total force would vary with the other; that is to say, it would be as the distance inversely, supposing the direct force to continue according to that law (214). Thus (216), suppose at distance $\frac{1}{2}$, force n became $2\,n$, whilst force p remained unchanged, we should then, calling force at a unit of distance $a \times b$ as before, have the force at distance $\frac{1}{2} = 2\,a \times b = 2\,a\,b$; that is to say, the distances being as 2 : 1, the force would be as 1 : 2. A similar reasoning applies to all the other cases (217, 218, 219). It is, however, more in accordance with observation to suppose the two forces to vary together.

221. The reciprocal attraction between the opposite poles of two magnets differs only, from that of the force exerted between a magnet and iron, in degree of distant action, not in kind. By the presence of permanent polarities in both the opposed surfaces, instead of in one only, the inductions upon which the subsequent attraction depends are greatly facilitated. In the force as exerted between a magnetic pole and mere iron, the pole n, Fig. 106 (209), upon which the reflected

force depends, has first to be produced; that is to say, the magnetic forces resident in the iron (14) must be first developed, and a portion of one of them determined in the direction of the magnet; whereas, in the reciprocal force between opposite magnetic poles, this portion of the attractive process is already complete, and the remaining part is a determination of the opposite forces in each bar in the direction of the opposed poles (210). In this case the limit of the distance at which the forces act is very considerably increased; by employing a small and powerful trial magnet in the balanced beam, Fig. 107 (212), we may obtain indications of measurable force at a distance of 10 inches or more; with delicately suspended needles and large magnets, Scoresby obtained indications of force at distances of 50 or 60 feet.

222. If we proceed to investigate the laws of magnetic repulsion, as exerted between similar magnetic poles (31), we shall find the same mutual play of reciprocal inductive force, as in the case of attraction; with the exception that the tendency of the inductions is in a contrary direction to that of the existing magnetic developments, Fig. 18 (28), and consequently to subvert the opposed poles; now the resistance to this subversion by the already established polarities, is probably the source of the repulsive effect (31). In conformity with this result, if we present to the pole of the magnet M, Fig. 109, whilst acting on the trial cylinder *t*, the similar pole of a second magnet *m*, the force on the trial cylinder will appear to increase. This is in fact the converse of the result already adverted to (213); here the tendency of the induction is (14) to repulse the similar polarity, and so increase its operations in other directions; we could hence deduce the law of this induction by observing the increase or decrease of the force upon the suspended cylinder, as the distance between the two magnetic poles is varied.

Supposing the laws of the inductive force to be the same

as before (214), let the similar poles of two magnets A B, Fig. 106, be opposed to each other, and let the small space n be taken to represent the amount of the subversive tendency on the magnet B, and the small space p that on the magnet A, then calling all the active magnetic particles in $n = a$, and all those in $p = b$, and taking some distance $p\ n$ as a unit of distance, we have, according to a similar notation and reasoning before given (215), force at distance unity $=$ $a \times b$; supposing the induction to vary as the distance inversely, and the polarity to remain unchanged, it will be at distance $\frac{1}{2} = 2\,a \times 2\,b = 2^2\,a\,b = 4\,a\,b$; at distance $\frac{1}{3}$ it will be $= 3\,a \times 3\,b = 3^2\,a\,b = 9\,a\,b$, and so on; according to the law determined by Coulombe (207); that is to say, the resulting force will be as the second powers of the distances inversely, and which may be verified experimentally by means of the two magnetic instruments (212) employed in all the preceding experiments; similar instead of dissimilar magnetic poles being opposed to each other, and a limit of distance being taken, such as does not affect the existing and established polarities. If in this, as in the former case of attraction, we suppose the inductive action to vary (214), then we may obtain laws of force according to other inverse powers of the distance. In fact, we may suppose the induction to be such, as will give any law of force, consistent with the nature of magnetic action. It is not, however, probable, from the peculiar character of magnetic repulsion, that any law of force in a greater inverse ratio than that of the second power of the distance would be likely to obtain, although the force may be frequently found to vary, as is commonly the case, in a less ratio; as, for example, in the inverse ratio of the simple distance, a very common law of repulsive force at comparatively small distances.

223. We have further to observe, that from the circumstance of the total repulsive power being dependent on the permanency of the opposed polarities, and on their relative intensity, we may infer, that in the case of opposed polari-

ties of very unequal force, the weaker may, at some limit of distance, yield to the inductive action of the stronger, and so an opposite, but weak, polarity may become induced upon the subversion of the polarity before existing. In this case the increments in the repulsive force would continue to decline, and the repulsion would at length be superseded by a weak attraction. This result is especially seen in Muschenbroek's experiments before quoted (188), and is easily obtained by means of the hydrostatic magnetometer, with magnets of very unequal force.* Indeed, it is no uncommon case to find two magnets repel at some distances, and attract at others. Even if we employ two magnets of precisely equal power, the tendency is always to a mutual reversion of their poles: and this tendency is so powerful as the distance between them becomes considerably diminished, that in no case do they remain unchanged. Under such conditions, therefore, experiments with repelling poles of opposed magnets would be open to considerable disturbance, and the results, as observed by Muschenbroek, not conformable to any regular law of force (184).

224. On a careful review, then, of these investigations, we find a fair solution of the seeming contradictions and differences in the results of experiments on the law of magnetic force, by many eminent philosophers, alike distinguished for their scientific learning and experimental ingenuity; and they appear to verify, in a remarkably clear and satisfactory manner, the truth of the deduction arrived at by the celebrated Brook Taylor, viz.: "That magnetic attraction, as commonly observed, is quicker at greater distances than at small ones, and different for different magnets;" which taking the facts as they present themselves in the ordinary way, is undoubtedly the case; and is, if the principles we have laid down be exact, not merely an experimental fact, but a necessary result of the elementary laws of magnetism (209, 214).

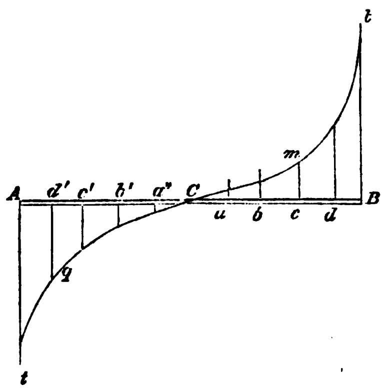
* Edinb. Phil. Trans. for 1829, p. 37.

It is, perhaps, to be regretted, that from a pre-disposition to identify the law of magnetic attraction with that of central forces generally, several profound writers have been led to question the accuracy of every result opposed to such a deduction. Thus, it has been said of Newton, who found the force of magnetism nearly as the cubes of the distances inversely (181), that he had very inaccurate ideas of magnetic phenomena.* It would be very difficult, however, to show from the little which this great author has advanced on this subject in his immortal work, the *Principia*, in what his notions were defective; on the contrary, they appear to be in most perfect accordance with experiment, and true to the letter. In associating magnetic action with a law of the centrifugal forces of particles terminating in particles next them, Newton never pretended to offer any theory of magnetism, but says, with his usual diffidence, "whether elastic fluids do really consist of particles so repelling each other is a physical question," which he leaves philosophers to determine. On the other hand, the learned Dr. Robison is led to question the accuracy of all the results produced by Hawksbee, Brook Taylor, Muschenbroek, and others (182), conceiving them to have been defective and injudicious; and further states, as we have already observed, that magnetic attractions and repulsions are not the "proper phenomena for declaring the precise law of variation." Yet it was by the means of these very same attractions and repulsions that Lambert, and more especially Coulombe, deduced what this accomplished author considers to be the true law of Magnetism.

225. *Law of Force in different Points of a Magnetic Bar.* —We have seen (25) that the polar forces in a magnetic bar decrease rapidly as we recede from the extremities, and at last vanish in a point termed the magnetic centre. If, therefore, we erect, between the magnetic centre and pole, Fig. 110, a series of perpendiculars or ordinates, *a b c*, &c.,

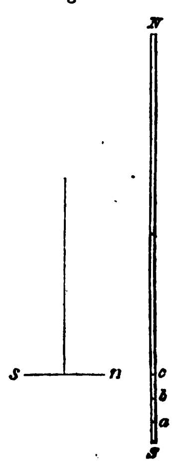
* Edin. Encyclopædia, vol. xiii. p. 270.

Fig. 110.



a′ b′ c′, &c., such as may represent the force in given points, then it is certain these lines will increase rapidly as we approach the poles A B, and we should, in passing a line through the extremities of these perpendiculars, obtain for the force of the north and south polarities, some such curve as that represented in the figure by the lines C *m t*, C *q t*, the ordinates being nothing in the centre C. Coulombe endeavoured to determine the value of these ordinates in the following way: —

Fig. 111.



Having determined the times of oscillation of a delicately suspended needle, *s n*, Fig. 111, a long magnetic wire, S N, was then placed vertically in the line of the magnetic meridian, immediately opposite the needle, the dissimilar polarities being opposed to each other. This would not of course change the direction of the needle; it would only affect the rate of vibration (139). The needle was now caused to vibrate opposite various points, S *a b*, &c., of this linear magnet, and at a constant distance from it. Then, taking the forces as proportionate to the square of the number of vibrations (139), and deducting the constant force previously determined, and by which the needle vibrates when the magnet S N is away, we

obtain the force due to any given point *a*, *b*, &c. In this experiment Coulombe supposes that the resulting force, as thus determined, is very nearly that of the point opposite which the needle vibrates; for, if we suppose the oblique forces of other points *a*, *c*, on each side of a given point *b*, to influence the result, still one-half the sum of the equidistant oblique actions will not be very different from that of the given point *b*; for if the points on one side *a*, are more powerful, those on the other are more weak; and whatever be the nature of the curve c *m t*, Fig. 110, which joins the ordinates, we may consider any very small portion, *m*, as a straight line. When, however, we come to the extremity of the wire or pole s, then, because there is no point outside it, as in the other cases, he doubles the number representing the square of the number of oscillations, by which artifice he renders the experiment for points near the pole comparable with the others. The curve of intensity thus traced by Coulombe, is a species of curve termed the logarithmic curve, the ordinates of which *a*, *b*, *c*, &c., Fig. 110, are in geometrical progression, whilst the abscissæ, c *a*, c *b*, &c., corresponding to these ordinates, are in arithmetical progression.* M. Biot, who treats this question from Coulombe's manuscripts, concludes that this result is a necessary consequence of the law of magnetic force being as the squares of the distances inversely, and that magnetism, like electricity, is little sensible in a body of regular figure before we approach its extremities, when it increases very rapidly.

226. The results and progress of Coulombe's investigation are, it must be admitted, neither so perfect or so satisfactory as could be desired, owing probably to the many difficulties

* That is to say, the abscissæ or distances c *a*, c *b*, c *c*, &c., Fig. 110, increase by the constant addition of some given number 1, 2, 3, &c., as the case may be, and the corresponding perpendiculars or ordinates, *a*, *b*, *c*, *d*, &c., by a continued multiplication by some given number, 2, 3, 4, &c.

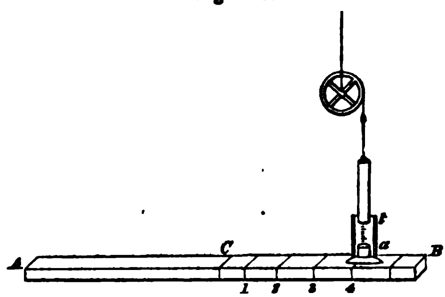
which embarrass the experiment, and the uncertain condition of the line of particles of the steel as to temper and other circumstances. It is therefore doubtful whether the logarithmic curve really represents the law of intensity from the middle point of the axis toward both poles. Lambert considers the force of each transverse element to be directly as the distance from the centre, whilst Robison, who repeated Lambert's experiments, imagines that this is only true for certain magnets. The results of Hanstein's inquiries (208), before quoted, go to prove, that the power of the distance representing the increase or decrease of the magnetic intensity between the centre and the poles of a magnet, agrees most perfectly when that power is taken = 2, or that the intensity of any magnetic particle situated in the axis is proportional to the square of its distance from the middle point of that axis.

227. Much uncertainty appears to have attended these inquiries, in consequence of a want of due attention to the regularity and temper, and the regular development, probably, of the magnetism throughout the bar. It is well known that bars not regularly and equably tempered, or only hardened about the extremities, will not retain any magnetic power except in the tempered parts. In other cases of very long bars, to which an adequate power for their complete magnetizing has not been applied, we have what has been called by Van Swinden culminating points, that is to say, they appear to consist of a series of magnets with opposite poles in contact; added to this, the investigation has been further embarrassed by the methods of experiment; these have been more or less indirect and liable to uncertainty. We may however, by a careful and skilful experimental arrangement, arrive at a fair approximation to the law in question, and in the following way:—

Exp. 57. Let a steel bar, A B, Fig. 112, of uniform texture, about 20 inches long, 1 inch wide, and ·3 of an inch

thick, be very carefully and equably tempered throughout its entire length, and rendered powerfully magnetic by the usual process (20), and in such way as to bring the magnetic centre C (26), as nearly as possible in the centre of the bar. Verify the position of this centre on the upper surface A B, by

Fig. 112.



the process described (28) Exp. 12, and divide that surface on each side the centre C into a given number of equal parts by lines 1, 2, 3, 4, &c., continued down over one side of the bar. These divisions may be about an inch and a half apart. The bar being thus prepared, place it edgeways on the table of support represented Fig. 78 (129), under the trial cylinder *t*, the divided surface A B being uppermost. Examine the forces at successive points 1, 2, 3, &c., through a small cylindrical armature of soft iron *a*, of the same diameter above as the trial cylinder *t*, and about ¾ of an inch or more in height, and at a constant distance, *a t*, this armature being fairly applied to the surface, and so as to cover a small space on each side of any given division. The square root of the force thus taken in degrees on the graduated arc of the instrument (126) will very nearly represent the comparative magnetic development. We may, in fact, observe, that by means of the armature *a*, we place the trial cylinder sufficiently beyond the influence of other parts of the bar, whilst the action becomes reduced to two points *a t*, or nearly so. Then, with respect to the armature itself, we may further observe, that supposing the resulting force to be partly derived from

the oblique forces on each side of it, still those forces would be very inconsiderable as compared with that of the point actually covered by the armature. Besides, as remarked by Coulombe (225), if we conceive the points on the side next the centre to be less forcible than those next the pole, still half the sum of all the equidistant forces would come very near the force of the point immediately under the armature, at least for a long series of points, extending from the centre c, but not carried quite up to the extremity of the bar. We may therefore obtain in this way such an approximation as will leave no doubt as to the law we seek to discover.

The experiment thus carried out gave the following results, the distance *a t* being ·3 of an inch:—

Distance from centre	1	2	3	4	5
Force in degrees	1	4	10	17	28
Magnetic development, or square roots of forces	1	2	3·1	4·12	5·29

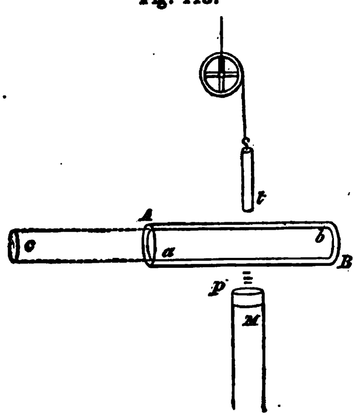
It appears, therefore, by these results, that the magnetism in different points of a regularly tempered and magnetized steel bar, of uniform texture, is directly as the distance from the magnetic centre; whilst the reciprocal force between any given point and soft iron is as the square of the distance from that centre. The distinction is important as regards all the preceding investigations, which may be taken to refer exclusively to what may be termed the intensity (229).

228. *Laws of Magnetic Charge.*—Magnetism, like electricity, appears to be a species of force confined to the surfaces of certain bodies without any relation to their mass. Its accumulation, however, or rather development, in tempered steel, rather partakes of the form of electrical excitation, than that of accumulation on insulated conductors; when developed in soft iron by influence (33), the development is very analogous in character to that of electrical induction by the influence of charged upon neutral con-

ductors. Now, although the terms magnetic charge, quantity of magnetism, and such like, may appear to convey a very hypothetical meaning, they are yet, if taken in the ordinary acceptation of such terms, as applicable to magnetic as to electrical action, since there must necessarily be some element of magnetism corresponding to the general term quantity, as expressive of the relative or absolute amount of the agency in operation, and upon which the observed phenomena depend. We have not, however, hitherto arrived at quantitative measures in magnetism, which, like the unit measure in electricity, determines the quantity of charge conveyed to coated glass. We know not, in fact, by the ordinary processes of magnetizing, what the relative quantities of magnetism may be, as developed in various bars; hence the investigation of such measures is of no small importance to the progress of magnetic inquiry.

By magnetic charge, then, we are to understand the amount or quantity of magnetism existing in a bar of tempered steel or iron, under a given attractive force, and which we may, as in electricity, term intensity. The following experiment shows that this intensity is independent of the mass of a magnetized body; and that consequently the magnetic development is entirely confined to the surface.

Fig. 113.



Exp. 58. Let A B, Fig. 113, be a small cylinder of soft iron, about 2 inches long, $\frac{1}{2}$ an inch in diameter, and $\frac{1}{10}$ of an inch thick. Let *a b* be an interior solid cylin-

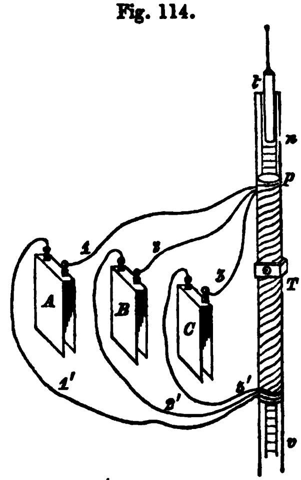
der, also of soft iron, closely applied to the interior surface of the external cylinder A B, but capable of being drawn out to any point *c*, or otherwise removed altogether. Let now this joint cylindrical mass be attached to a divided scale, and a magnet M, fixed at a constant distance *p* immediately under it, bring the whole immediately under the trial cylinder *t* as represented in the figure, and according to the arrangement more fully shown Fig. 77 (129). We may then estimate by the attractive forces on the trial cylinder *t* any change of intensity in the induced magnetism, the cylinder A B being taken either hollow or solid, or influenced by a greater or less extent of surface *c* A B. Things being thus arranged, and the distances *p* and *t* being regulated to within $\frac{3}{10}$ of an inch, the following results were obtained:—The force, as observed, with the joint cylinders A B and *a b* taken together as a mass, amounted to 10°; under this attractive force, the interior cylinder *a b* being extended toward *c*, the intensity or force on $t = 10°$ gradually declined; when the surface extended to the greatest limit *c* the intensity was only $\frac{1}{2}$ as great, the force then being only 5°. On removing the interior cylinder *a b* altogether, the intensity again returned to 10°, being precisely the same as at first. We may hence conclude that Magnetism, like Electricity, is influenced only by surface, and is altogether independent of the mass: a deduction, further supported by the fact that a hollow tempered steel cylinder acquires as great magnetic power by the ordinary process of magnetizing, as a solid tempered steel cylinder of the same dimensions.

229. Magnetism then being a development confined to the surface of magnetic bodies, we require to determine its intensity in respect to the quantity developed, and the extent of surface over which it is disposed. In reviewing the deductions (215) bearing on the law of magnetic attraction, it may be observed that the reciprocal force is always as the square of the induced magnetism; that is to say, as the square of the quantity of magnetism brought into opera-

tion. Thus, where the force is in the inverse duplicate ratio of the distance (215), when induction $= n$, we have force represented by $a\,b$; when n becomes $2\,n$, force $= 2^2\,a\,b$; when n becomes $3\,n$, force $= 3^2\,a\,b$, and so on: that is to say, whilst the inductions or quantity of magnetism developed are 1, 2, 3, &c., the reciprocal forces of attraction or intensities are 1, 4, 9, &c.: the same is observable in any of the other laws of force. Take, for example, the case in which the force is as the cubes of the distances inversely (218): when induction $= n$, force is $= a\,b$; when n becomes $2\cdot83\,n$, we have force $= 2^3\,a\,b = 8\,a\,b = \overline{2\cdot83}^{\,2}\,a\,b$; when n becomes $5\cdot2\,n$, force is $3^3 a\,b = 27\,a\,b = \overline{5\cdot2}^{\,2}\,a\,b$; that is to say, whilst the quantities of magnetism induced are as the numbers 1, 2·83, 5·2, &c., the forces are as the squares of those numbers. We may from this infer, that to arrive at the quantity of magnetism in operation, all other things being the same, we must refer it to the square root of the attraction or intensity.

230. This deduction being a new and important feature of magnetic action, it may be as well to further verify it by something like a direct and quantitative process.

Fig. 114.



Exp. 59. In this experiment let A, B, C, Fig. 114, be three precisely equal and similar voltaic batteries on Smee's principle (47), each battery consisting of two elements, and charged with dilute sulphuric acid. Let T represent a cylinder of soft iron, about 8 inches long, and ½ an inch in diameter, attached to a divided scale $t\,v$, and surrounded

by three distinct coils of copper wire covered with silk thread, not superposed, but coiled successively round the iron. Let the extremities of these coils 1 1′, 2 2′, 3 3′, extend to each of the batteries A, B, C, so as to appropriate each coil to a corresponding battery; for example, coil 1 1′ to battery A, coil 2 2′ to battery B, and so on; the whole being so circumstanced as to admit of an easy connection, and so bring one or more batteries into action at pleasure. Let the iron cylinder T, thus circumstanced, be placed at a given distance *p n* immediately under the trial cylinder *t*, suspended from the wheel of the magnetometer (126) as in the preceding cases; then, as is evident, when either one or more of the batteries A, B, C are brought into operation through their respective coils, the iron T becomes magnetic (53); and hence arises a reciprocal attractive force between its extremity *p* and the trial cylinder *t n*, which force is represented in degrees of the graduated arc attached to the instrument (126). Supposing the batteries to be precisely equal and similar, and each to develop the same magnetic force when taken singly, we may infer that if one battery A, and one coil 1 1′, call up one quantity of magnetism considered as a unit of quantity; then two batteries A + B, and two coils 1 1′ + 2 2′, taken conjointly, will develop two quantities; three batteries and three coils will produce three quantities. To determine the law, therefore, as regards quantity, it only remains to observe the forces of attraction corresponding to these several developments.

The experiment thus carried out gave the following series of results; the distance *p n* being regulated at $\frac{8}{10}$ of an inch.

Batteries or quantity of magnetism	1	2	3
Force in degrees	4	17	37

We may here perceive that the intensity (force) is as the square of the quantity of magnetism, or very nearly; being precisely the same law as that deduced for electrical charge.*

* Rudimentary Electricity, (102), p. 118, second edition.

To obtain, therefore, the relative quantity of magnetism in operation, we must take the square roots of the respective intensities; the magnetic surface and all other things being the same.

231. Although this law appears pretty evident as respects the amount of magnetism in the same or equal magnets, we still require much further investigation of the law of intensity as regards dissimilar magnetic bodies of variable size and surface. The conformity of the previous law of magnetic charge with that of electricity would lead to the conclusion that the law of surface was also the same, and that the intensity would be as the square of the surface inversely;* that is to say, the same quantity of magnetism developed upon a double surface would have only ¼ the intensity. In the present state of magnetic research we can only look to this as being a highly probable result; since we have not any direct methods of experiment, as in electricity, by which such a law can be fairly verified, we require in fact to change the surface without interfering with the magnetism. Now this is not easily accomplished; if, as in Exp. 58 (228), we extend the surface, we are likely at the same time to change the amount of induced magnetism, and we get a mixed result; or if, in the last Exp. 59, we increase the dimensions of the iron cylinder T, we are not sure that the quantity of magnetism will remain the same. Until, therefore, some further means of investigating this question by experiment are at our command, we must be content with considering the law of charge as regards surface in the light of a high degree of probability.

Supposing these laws of magnetic charge so far established, we may conclude that if the respective intensities of two similar magnets, the surfaces of which are to each other in a given ratio, say as 1 : 2 be the same, then the quantities of magnetism in each will be in the same ratio, that is also as 1 : 2; for whilst the intensity increases with

* Rudimentary Electricity, (114) (115), pp. 134, 135, second edition.

the magnetism, it decreases with the surface; and hence with twice the quantity of magnetism upon twice the surface, it remains unchanged; being precisely the same law as that of the accumulation of electricity on coated glass, in which the intensity of a whole battery is no greater than that of one of the elementary jars taken singly.

232. We must not, however, confound this result with a collection of charged jars, or a combination of magnetic bars, each jar or magnet operating independently of the others. What is termed a magnetic battery (19, 115) differs essentially from the electrical battery. It is in fact a mere assemblage of magnets, the resulting intensity approaching in a greater or less degree the sum of the intensities of the whole series; no one magnet forms, as it were, any part of any other magnet; whereas, in the electrical battery, all the jars are united, as it were, into one great whole through the charging rods; and the intensity is no greater in the whole combination than in any one jar taken singly.* To assimilate the action of a number of charged jars with that of a combination of magnets, the jars must be separate, and each brought to operate independently of the others. Imagine, for example, a light-conducting disc, of 6 inches in diameter, poised and suspended from a common balance, then if we place a small charged jar immediately under it at a given distance, the balance will indicate a given force. Let a second similar jar be now placed by the side of the former, then the attractive force will be twice as great, and so on; until we have filled an area exactly equal to that of the suspended disc. We may further conclude that the relative magnetism, in two precisely similar and equal magnets, will be as the square roots of their respective intensities (229), as determined by either of the magnetic instruments (212) employed in these researches.

233. *The Magnetic Curve.*—The two forces developed in

* Rudimentary Electricity, (117), p. 139, second edition.

a magnetic bar, and resident in its surface, give origin in operating on each other through particles of ferruginous matter, to certain curved lines of force, as indicated (28) Fig. 16. These lines were originally considered as the "curvature of the magnetic current," under an impression that they originated in the circulation of a subtle fluid about the poles of the magnet. Although this hypothesis is now but little valued, yet, as observed by Lambert, we must admit the existence of the curves, and may, without any very great violation of language, call them curves of the magnetic current; it is not the name which constitutes the difficulty; whatever name we give them, we have still to determine the nature and properties of the curves.

This very beautiful physical question constitutes, as before observed (202), the principal feature of Lambert's fine mathematical paper in the Berlin Memoirs, and has further engaged the attention of several eminent philosophers. Dr. Roget, the talented author of the treatise on Magnetism, published by the Society for the Diffusion of Useful Knowledge, has also treated this question with considerable ability. Not only has he given many interesting demonstrations of the fundamental properties of the magnetic curve, but has also described a mechanical instrument for generating them.* In referring to Figs. 16, 17, 18 (28), we may perceive that the magnetic curve is either convergent, as in Figs. 16 and 17, or divergent, as in Fig. 18, according as we employ one or more magnets, and according as we refer the forces to similar or dissimilar poles. If we conceive, Fig. 16, each small particle of iron to be an indefinitely small needle free to move in any direction, it would necessarily arrange itself in a given determinate position in respect of the forces in action. In fact, it may be demonstrated, that supposing the magnetic force to vary in the inverse duplicate ratio of the distance, the direction of the

* Journal of the Royal Institution, February, 1831.

axis of a magnetic needle, placed at a given distance from the centre of the magnet, will be always a tangent to the point of curvature of one of those peculiar oval curves indicated in the figure (28). Taking, therefore, the ferruginous particles as indefinitely small magnetic needles, we may conceive the line of curvature at any given distance from the centre as made up of a series of such small needles. With respect to the curve itself, it may be considered, geometrically, as generated by the movement of two lines A C, B C, Figs. 115 and 116, termed radiants, and which revolve about the poles A B, with angular velocities proportional to the varying distances A C, B C, from the point of intersection C. Let, for example, the two radiants A C, B C, be supposed to turn about the poles A and B, and let them have moved together into the positions A *c*, B *c*, then if angle C A *c* be to angle C B *c* as A C to B C, the points C *c* will be points in the magnetic curve.

Fig. 115.

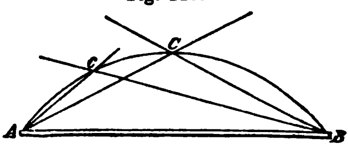
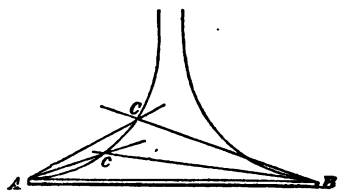


Fig. 116.



The direction of the motion of these radiants, A C, B C, may be, as is evident, either in the same, or in opposite directions. When in opposite directions, as in Fig. 115, both the polar angles, C A B and C B A, increase together, and the curve is convergent; in this case we have a single continuous branch A C B. When, however, the radiants revolve in the same directions as in Fig. 116, then whilst one of the polar angles C B A increases, the opposite angle C A B decreases; in this case the curve is divergent, and

finally resolves itself into two divergent branches, as shown in the figure.

The magnetic curve possesses several very interesting geometrical properties, as may be seen in Leslie's elegant work on Geometrical Analysis;* we have not, however, sufficient space to admit of a more general exposition of this subject. According to one of the principal properties of this curve, the sines of the angles made by a tangent and the radiants, drawn to the point of contact, are proportional to the square of the radiants. Thus, supposing a tangent drawn to the point C, Fig. 115, we should have the sines of the angles formed with C A and C B :: $A C^2 : B C^2$. In the construction of this curve we require to find points in which a small needle being placed, its direction will be a tangent to the curve.

234. We must not conclude our account of these several inquiries into the nature and laws of magnetic force, without an especial notice of Professor Barlow's very important investigations of the action of spherical and other masses of iron, on the compass-needle, remarkable not only for the precision and elegance of the experiments which they contain, and the mathematical learning and address which they display, but also as furnishing one of those rare examples of physico-mathematical research alike important to the student and to the progress of science.

These researches were commenced soon after the appearance of Hanstein's work in 1817 (208), and were undertaken with a view of correcting the errors arising out of the attractive influence of the iron of a ship on the compass.

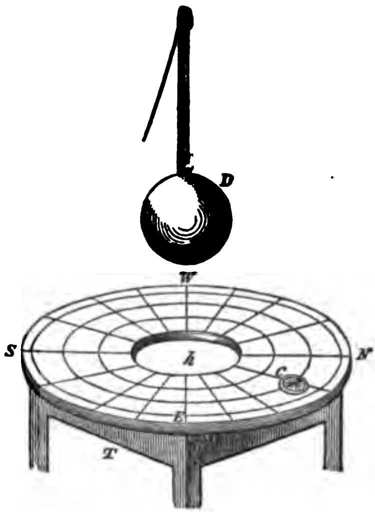
As a preliminary experiment, an iron shell, such as used in the common howitzer mortar, was placed in different positions about a compass (143), considered as a centre of position, and the deviation of the needle noted both as regarded quantity and direction. Now it was soon disco-

* Page 399.

vered that the deviation depended on the position of the centre of the shell in respect of the centre of the needle, the shell being elevated or depressed in a given vertical, so as to place its centre alternately above and below the needle, the deviations of the needle were observed to be in opposite directions; that is, they were first easterly and then westerly, or reciprocally. Now this happened in every azimuth plane (149), except the plane of the magnetic meridian. In this plane the compass maintained its true direction. From these changes in the deviation it followed, that in carrying the shell about the compass, and elevating or depressing it, in different vertical planes, a point would exist in each plane, in which the deviation would vanish, since the deviation could not possibly change from an easterly to a westerly deviation without passing through a point of neutrality. In the azimuth, east and west, at right angles to the magnetic azimuth or meridian, the deviation was nothing at the line of intersection of the magnetic with the horizontal plane, that is in the east and west line. In this line the needle also took its natural direction. Now it occurred to Professor Barlow, that if a great number of points of no deviation were thus determined, they might all be in the same plane, which plane would probably in these latitudes be inclined to the horizon; for, since only two opposite points of no deviation were observed in the horizontal plane, it could not evidently be parallel to the horizon.

235. With a view to a more perfect experimental investigation of this interesting question, Professor Barlow contrived a new form of the experiment. His apparatus is represented in the annexed Fig. 117. A plane table T, about 4 feet 8 inches in diameter, fixed on massive pillars, being covered with fine paper, has several concentric circles drawn on it. The circular plane is divided into 144 equal parts by radii drawn to every $2\frac{1}{2}°$ of the circumference, and all parting from one principal diameter N S, taken in the line of the magnetic meridian. The centre of this table is a distinct

Fig. 117.



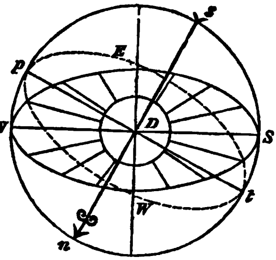
circular piece of 18 in. diameter, which may be removed so as to leave an opening for an iron ball or shell D, weighing about 288 lbs., and hung on a set of Smeaton's pulleys. Things being thus disposed, a compass C is placed on one of the concentric circles of about 20 inches radius or distance from the centre, and the deviations under the influence of the iron ball D observed at each 5°, in different azimuths, that is, in carrying the compass quite round the circle. By elevating or lowering the ball, the height or depth of its centre, above or below the centre of the compass needle, in the various points of no deviation, could be easily determined. The result of this experiment clearly proved that the points of no deviation are all in the same plane, which plane is inclined to the horizon at an angle of about 20°, being the complement of the angle of the dipping-needle (153), that is, the quantity required to complete 90°, the dip being about 70° (158).

It is quite clear that this method of observation is virtually the same as the former (232), the difference being, that we circulate the compass about the ball, instead of carrying the ball about the compass, and instead of elevating or depressing the centre of the needle, we raise or lower the centre of the ball.

236. It may perhaps facilitate the conception of this extremely beautiful experiment, and the results arrived at,

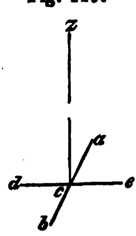
if we suppose the ball D, Fig. 117, to be fixed in the centre of the table T, one half being above, the other half below the plane of the table, as shown in the next Fig. 118, and then imagine the compass to be circulated about the ball. The experiment would then stand as in Fig. 118. In this figure let N E S W be the horizontal plane of the table, D the iron ball. Let *s n* be the direction of the dipping-needle (153), Fig. 92; N *s* S *n* the magnetic meridian, and N S the direction of the horizontal needle. Now we are to suppose the compass to be circulated about the ball D in a circle of a given radius, say 20 inches, and its centre elevated or depressed above or below the horizontal plane at each azimuth of 5° (149), as the case may be, until the deviation vanishes. In this case the centre of the compass would be found to have moved in the plane *t* E *p* W, inclined to the horizon N E S W, about 20°, and perpendicular to the direction *n s* of the dipping-needle.

Fig. 118.



Our conceptions of this experiment may be still further enlarged, if, instead of the horizontal needle, we suppose a small dipping-needle to be circulated about the ball, prepared as in the annexed Fig. 119; in which, let *a b* be a very small magnetic needle, centrally suspended by a delicate thread *z c*, and crossed at the centre *c* by a horizontal index *d e*, consisting of an extremely light reed, or a bristle. If this needle be circulated about the ball D, Fig. 118, as before, the index *d e* will exhibit the same deviations as the horizontal needle, whilst the relative position of the inclined needle in respect of the polar axis

Fig. 119.



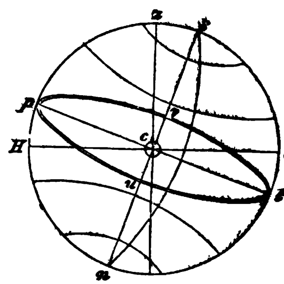
n s of the ball D, will materially assist our comprehension of the results.

Let us then imagine this needle, *a b*, Fig. 119, to be in the point W, Fig. 118; it will in this point have no deviation (234); here the line of direction or axis of the needle being parallel to the polar axis *s n* of the ball, and the line D W, joining their centres being their perpendicular distance, all the attractions upon the needle will balance. Directly, however, we move the needle out of this position, the same conditions do not arise, except the centre of the needle move in the plane W *p* E *t*. It is only in this plane that the direction *a b*, Fig. 119, of the needle, and the polar axis *s n*, Fig. 118, of the ball D, remain parallel, and their centres always at the same perpendicular distance. We see, therefore, why it is that the points *p t*, in the magnetic, and points E W, in the horizontal plane, are points of no deviation. They are, in fact, all points in the plane of equal attraction, or neutrality, as we may also term it. The east and west points in the horizontal plane are the points of intersection of the two planes. There is, however, this difference between the inclined and horizontal needles when placed in the magnetic plane N *s* S *n*; except in the points *p s t n*, the inclined needle varies, in the course of circulation about the ball D in that plane, much in the same way that the horizontal needle deviates in being carried round the ball D, in the horizontal plane. Now every point in the magnetic plane is a point of no deviation for the horizontal needle (234), but not for the dipping-needle (236); hence, for the horizontal needle we have two planes of no deviation, the inclined plane *p* E *t* W, and the magnetic plane N *s* S *n*. It is, however, the inclined plane which we are to consider as the plane of no deviation *par excellence*, because in this plane neither the dipping-needle nor the horizontal needle deviates, whereas in the magnetic plane there are only four points of no deviation for the dipping-needle, viz., the

points p E t W, and these are, after all, points in the plane of neutrality; besides this, the cause of no deviation of the horizontal needle in the magnetic plane is of a very different kind from that of the cause of no deviation in the inclined plane, which has a peculiar and distinctive character.

237. Since the neutral plane evidently cuts the surface of the ball in a great circle, $p\ u\ t\ v$, Fig. 120, the plane of which passes through the centre C,—this great circle has been called by Professor Barlow the magnetic equator, the axis and poles of which are coincident with the line $s\ n$ of the dipping-needle. The hemisphere $p\ n\ t$, below the equator $p\ t$, he calls the north magnetic hemisphere, and the opposite hemisphere, $p\ s\ t$, the south magnetic hemisphere. Any point on the sphere is distinguished by its magnetic latitude and longitude, to which end, parallels of magnetic latitude and meridians of longitude are drawn, as on the common globes. Extending the plane of these circles, they may be conceived to cut an ideal sphere, $p\ s\ o\ n$, concentric with and surrounding the ball c, and may be hence employed to define the magnetic position of any point in space with reference to the centre c of the sphere.

Fig. 120.



In circulating a compass about the ball in any of these lines or circles, Professor Barlow found, as he had anticipated, that the greatest amount of deviation was in the meridian circle passing through the east and west points; on this account he takes this meridian as his first meridian, and calls its longitude zero. Instead of imagining an ideal astronomical sphere, $p\ s\ o\ n$, to surround the ball c, and in given points of which the compass may be supposed placed, it will be in some cases more convenient to imagine such a

sphere to surround the centre of the compass placed at c; and suppose the ball moved into certain points of longitude and latitude, the practical result will be evidently the same, and reference may be made to either at pleasure.

238. Very numerous experiments and comparisons between the trigonometrical lines (182) of the angles of deviation and those of the latitude and longitude of the point in which the compass or ball is placed give the following results; and which apply to regular as well as irregular masses of iron.

1°. The longitude being zero, that is the compass or ball being anywhere in the great circle passing by the east and west points (235), "the tangent of the angle of deviation is proportional to the sine of the latitude multiplied by the cosine, or to the sine of the double latitude."*

2°. The latitude being constant, "the tangent of the deviation is proportional to the cosine of the longitude."

3°. The latitude and longitude being both varied, "the tangent of the deviation is proportional to the cosine of the longitude multiplied into the sine of the double latitude."

If we denote the deviation by Δ, the latitude by λ, and the longitude by l, we have these laws thus algebraically expressed:—

$$\text{Tang. } \Delta = \sin. 2\,\lambda. \quad \text{Tang. } \Delta = \cos. l.$$
$$\text{Tang. } \Delta = \sin. 2\,\lambda \times \cos. l.$$

The laws of attraction with respect to distance and force, were found to be as follows:—

$$\text{Tang. } \Delta = \frac{1}{d^3}. \quad (\text{Tang. } \Delta)^2 = F^3. \quad \text{Tang. } \Delta = F^{\frac{3}{2}}.$$

in which the distance is denoted by d and the force by F.

It is to be understood that these laws are only calculated approximatively, they are positively correct only for a needle indefinitely small, and placed at a limit of distance from the iron ball, such that the magnetism of the needle, and that

* The product of the sine and cosine of an angle is = to the sine of twice that angle.

of the ball, as depending on the induction of its position (101), may operate on each other in the way of two magnets. If we bring the needle very near the ball, then the induction of the magnetism of the needle upon the iron is such as to supersede this action; and instead of attracting one pole of the magnetic needle and repulsing the other, it will attract either pole of the needle indifferently, or nearly so (222).

239. This action of an iron ball on the compass-needle, contrary to Professor Barlow's expectations, was found independent of the mass, and to relate only to a small thickness of surface. The following are the results as regarded balls or shells of different magnitudes:—

1°. The tangents of the deviations are proportional to the cubes of the diameters of the shells or balls; so that we have, in denoting the diameter by D, Tang. $\Delta \propto D^3$.

2°. The tangent of the deviation is as the $\frac{3}{2}$ power of the surface. Hence, if we denote the surface by S, we have Tang. $\Delta \propto S^{\frac{3}{2}}$.

These laws are apparent whatever be the weight or thickness of the shell, provided its thickness be not less than the $\frac{1}{30}$ of an inch.

Although the conclusion that Magnetism resides wholly on the surface of iron bodies appeared satisfactorily established in this kind of action, yet Professor Barlow considers "further experiments necessary to establish the fact." Such experiments we have already adduced (228), and they confirm in a very striking way the truth of this deduction.

Our limits will not admit of any further account of these most valuable researches into the laws of magnetic forces, which the student will find very clearly and explicitly detailed in Professor Barlow's work on "Magnetic Attractions." We shall, however, have again occasion to refer to their practical and theoretical application under another branch of our subject.

VII.

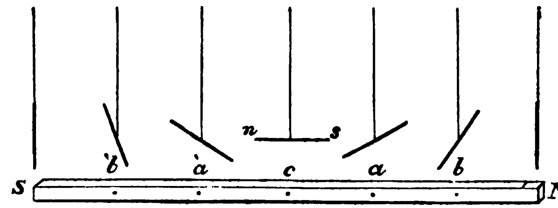
TERRESTRIAL MAGNETISM.

The Earth a Magnetic Body—Variation, Dip, and Intensity, the three Forms of its Magnetism—Phenomena of the Horizontal, Inclined, and Oscillating Needles—Variation of the Compass—Magnetic Charts—The three kinds of Magnetic Lines—Course of the Terrestrial Magnetic Equator—Points of greatest Polar Dip—Points of greatest Polar Intensity—Position of the Magnetic Poles—Magnetic Disturbances.

240. Comparing the phenomena of the horizontal and inclined needles (21) with those of ordinary magnetic action, we can scarcely avoid the conclusion that the globe of our earth is upon the whole a magnetic mass, and that it operates on those needles much in the same way as one magnet operates on another. We have seen (153) that in these latitudes the position of an evenly-poised and freely-suspended magnetic bar is not a horizontal position, but an oblique position, the north pole being inclined downward at an angle of about 69° with the horizontal line. Now, if we transport this bar to various parts of the earth, then this angle or dip varies, being nothing about the equatorial regions, where it is horizontal, and 90° in the regions of the poles, where it is vertical (21), that pole of the bar which turns toward the north being depressed in the northern hemisphere, and the opposite pole in the southern hemisphere; the following experiment is highly illustrative of the magnetic conditions of this phenomenon.

Exp. 60.—Let N S, Fig. 121, be a magnetic bar, 30 inches in length, about $\frac{1}{2}$ an inch thick, and 1 inch wide, we are to suppose this bar regularly magnetic and laid edgeways. Let *n s* be a short balanced needle of light iron wire or

Fig. 121.



magnetic steel wire, about 2 inches in length, suspended by a filament of silk, immediately over the magnetic centre C, so as to be a full length distant from it. At this point the needle will retain its horizontal position, its axis being parallel to the axis of the magnet beneath, and its poles *n s* in a reverse position to the poles N S of the bar (11). Under these circumstances let this small needle be gradually moved along, and over the magnetic surface N S, we shall then find it take different degrees of inclination, the inclination being greater as we approach either pole N S, at which points it will be 90°. We shall further observe, in the course of this experiment, that the south pole *s* dips on the north polar side of the centre C, and the north pole *n* on the south side. We have here only to conceive the longitudinal magnet N S to represent a portion of the earth's surface extending between the polar regions, and we have a series of phenomena very analogous to those of the direction and dip of the magnetic needle (21).

The magnetism acquired by a bar of soft iron when placed in a given position (101) is further indicative of the magnetic state of our planet. We have already seen (102), that, in placing a bar of soft iron in the position of the dipping-needle, it is immediately rendered sensibly magnetic; the lower extremity in these latitudes being a south pole, and the upper extremity a north pole. If the experiment be tried in the southern hemisphere, then the lower

extremity becomes a north pole, and the upper extremity a south pole. Now this is as near an approach to magnetic induction (33) as can be well imagined.

241. This magnetic condition of our planet, from whatever source derived, becomes more fully revealed to us through the medium of three classes of phenomena, viz., variation (7) (162), dip (21) (162), and intensity (228); these are the three great forms of the earth's magnetism. The absolute values of these elements, the changes to which they are subject, together with their mutual relations and dependencies, have now become the great objects of investigation, we may add to these certain irregular disturbances by which these elements are occasionally influenced, and which are more especially traced by means of the magnetic instruments and observatories already adverted to (169). In order, therefore, to investigate the magnetic condition of the earth, we require to know

1°. The declination or variation of the horizontal needle, by which we determine its correct position or direction at any given place.

2°. The inclination or dip, by which we determine the true line of direction of the magnetic force.

3°. The number which represents the ratio of the intensity of the force at any given place, to some comparative unit, by which we trace the general magnetic condition of the terrestrial surface.

242. The changes to which the earth's magnetic force is subject may be distinguished by the terms secular, periodical, and irregular. Secular changes are such as are slowly progressive and which run through a certain course in very long periods of time, returning finally to their original value. Periodical changes are certain regular changes or variations, happening in short periods of time, such as a day, a month, or even a year. Irregular changes are such as cannot be traced through any uniform

course and which are not apparently subject to any given law.

243. In pursuing this most important physical subject, we cannot do better than commence with the phenomena of the horizontal needle. Did the magnetic compass everywhere coincide in direction with the geographical meridian, and were its direction invariable, it would be one of the most simple and valuable instruments ever constructed; such, however, is not the case (162), its direction is not everywhere the same, it seldom coincides with the true meridian, and is beside subject to a variety of periodical and other variations.

The angular deviation of the compass from the true meridian, termed the declination or variation of the magnetic needle, was certainly known to the Chinese so long since as the commencement of the twelfth century. Keoutsoung-chy, a Chinese philosopher, who wrote on subjects of natural history about the year 1111, states that "the magnetic needle declines toward the east, and hence does not point straight to the south, but is only $\frac{5}{6}$ to the south." Pere Amiot, who resided at Pekin about the year 1780, remarks, in confirmation of this, and in reference to the north pole of the magnet, "the magnetic needle still persists in this capital in pointing 2° and 2° 30′ towards the west, which is still a peculiarity of this country." The Chinese say, in reference to the south pole, that "the needle declines eastward 2° and 2° 30′, that it is never more than 4° 30′, and never less than 2°."* An old manuscript in the University of Leyden, written in 1269 by Peter Adsiger, also notices the phenomenon of an east declination in the north pole of the needle.† The great Venetian pilot, Sebastian Cabot, in the service of Henry VII. of England, also Gonzales Oviedo and the celebrated Colum-

* Klaproth, Lettre à M. le Baron de Humbolt, p. 69.

† Cavallo on Magnetism, p. 317.

bus, and other early enterprizing navigators, all observed the deviation of the compass from the true meridian; indeed it could scarcely have escaped their attention, since they pursued tracts in the course of which the needle must have changed more than two points; the fact appears to have caused no small confusion and anxiety amongst the sailors who accompanied Columbus in his first voyage to America, the needle having hitherto been always supposed to point true north. It appears by Irving's most interesting work,* that, on the 13th of September, 1492, Columbus at nightfall found his needle pointing 6° to the west of the polar star. He again examined this deviation the next night, and found it to increase as he advanced—a circumstance which caused the greatest consternation and alarm; "it seemed as if the laws of nature were changing, and that the compass was about to lose its mysterious power." Columbus, however, quieted the fears of the pilots by telling them that the needle had its daily changes round the pole like the heavenly bodies. It is not a little remarkable that notwithstanding the frequency of these observations, mathematicians and others of that time who adhered to the system of the Aristotelian philosophy, gave little or no credence to these accounts, considering the thing impossible. At length, however, repeated observation no longer allowed the mere abstract philosopher to maintain the discussion, and in 1556 the declination of the compass was fully received by Spanish writers on navigation as an established fact.†

244. The first well-authenticated observations on the variation of the compass in England are to be found in a work by Borough,‡ comptroller of the navy in 1581, as also in a work by Norman, of the same date.§ They state, from observations at Limehouse in 1580, that the declination was

* Life of Columbus.

† Arte de Navegar. Valladolid, 1545.

‡ The New Attraction.

§ Discourse on Variation of Compass.

at that time 11° 15′ East. In the early part of the following century, Professor Gellibrand found the declination to be only 4° 5′ East; and in 1657 it appears to have vanished altogether. From that time to the year 1660 the magnetic needle did not sensibly deviate from the true meridian. About five years subsequently to this (viz. in 1665), the direction of the needle appears to have become about a degree and a half west of the meridian; and this westerly declination went on increasing up to the year 1818, since which time the needle has been again approaching the true meridian. The following table contains the declination with the mean rate of motion as referred to certain periods of observation in London between 1580 and 1850, comprising about 270 years.*

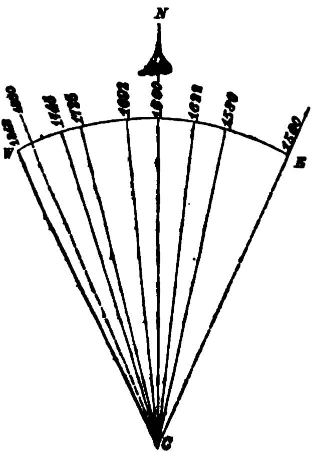
	East declin.		Zero.	West declination.				
Years......	1580.	1622.	1660.	1692.	1730.	1765.	1818.	1850.
Declination..	11° 15′	6°	0°	6°	13°	20°	24° 41′	22° 30
Rate per year	7′	8′	10′	11′	11′·5	9′	0′	5′

It may be perceived by this table, that for a period of eighty years from the first discovery the needle gradually approached the true meridian, and then for a following period of 158 years it travelled westward; having at the end of this period attained, in 1818, its maximum of westerly declination, viz., nearly two points and a half of the compass; it has ever since been retrograding, and is now moving again eastward. The mean rates of the movement at the different periods, although deduced from a long interval of years, may not upon the whole be far wrong; they serve at least to prove that the motion is not uniform. In approaching the meridian it has evidently become accelerated, and in approaching the maximum has become retarded; the present rate of decrease, as deduced by Dr. Lloyd at Dublin, is about 5′ annually. Thus it appears that the horizontal needle is

* The rate of movement has been deduced from the average rates of the intermediate periods.

subject to a variable oscillation across the line of the true meridian; the period of its westerly movement being about 160 years, and the limit of its angular variation 24° 41′. The annexed Fig. 122 represents this angular movement as hitherto observed, the extent of the whole movement being represented by the angle W C E, about 50°, that is, supposing the easterly semi-oscillation to have been equal to the westerly, and the first observations to have been made during the progress of the approach of the needle to the meridian C N, in the year 1580; this would make the total period of one oscillation about 320 years.

Fig. 122.



Observations made at Paris and other parts of the world give similar results; the direction and extent of the deviation, however, are not the same for all places; whilst in particular regions of the globe the needle is found to coincide always with the line of the true meridian. At this present time the declination is west throughout Europe. As we approach very high latitudes, the disturbance in the direction of the magnetic needle is very considerable. Parry, in his first voyage, observed a westerly declination of more than nine points of the compass.

245. A large number of observations on various parts of the earth, from the poles to the equator, on the sea and on land, prove that the lines of direction of the horizontal needle over the earth's surface are not alike. 2. That these lines are in a constant state of variation, some toward the east, others toward the west.

We are indebted to Halley, who was sent out by the government of William and Mary, to make observations on magnetic declination, for the first attempt to systematize the different variable directions of the magnetic needle. His method consisted in first marking on a general map of the world all those places in which the declination was nothing, and uniting the whole by a line, which he termed the line of no declination. He then traced in a similar way all the points in which the declination was 10°, 15°, 20°, and so on, east or west, thus representing by a magnetic chart the variation of the needle upon the surface of the earth so far as then ascertained, viz. in the year 1700. Many interesting and important results were derived from this system. It was observable, for example, that a line of no variation ran obliquely over North America across the Atlantic Ocean. Another line of no variation descended through the centre of China and passed across New Holland. From which he inferred that these lines had a communication near both poles of the world. Between these lines of no variation, that is, throughout all Europe, Africa, and the greater part of Asia, the declination was observed to be westerly, and on the opposite side, that is, over all the Pacific, it appears to have been at that time easterly. It was further observable, that the lines of greatest variation were confined to the polar regions, whilst the least encompassed the globe about the equator.

246. Lines of equal or of no declination, as thus traced on the earth's surface, have been called "Halleyan lines," in honour of their inventor; and more recently "Isogonal lines," or lines of equal angles. The map or chart on which these lines are traced has been termed a "variation chart," and is evidently an invention of no mean importance to the purpose of navigation. The first chart of this kind, constructed by Halley, has necessarily become obsolete, not only from errors arising from the imperfect state of magnetic instruments at the time of the observations,

but also from the now known variable state of the earth's magnetism. Halley's chart was first revised by Messrs. Mountain and Dodson, about 1756. Since this period we have had the magnetic atlas of Churchman, up to the year 1800, Hanstein's celebrated chart, published in 1820, and the variation chart and globe of Professor Barlow, which includes the observations of Captain Sir James Clarke Ross in the Arctic Seas. The latest chart of this kind is a chart by Erman, who has determined, from his own observations principally, the isogonal lines up to the years 1827 to 1830, throughout the whole length of the Russian empire; these later productions comprehend, not only the variation, but also the phenomena of the inclination and intensity of the force, and may be hence more properly denominated general magnetic charts than charts of mere variation.

The isogonal lines, as thus laid down on a chart, present to the eye a great variety of complicated flexures; they are seldom parallel to each other, a great portion of them appear to converge towards two points on the earth's surface, one near Baffin's Bay, the other to the southward of New Holland. In Hanstein's chart the isogonal lines exhibit a double convergence in the northern hemisphere toward two points in the vicinity of the pole indicated by the dipping-needle.

247. It has been ingeniously observed by Euler, that a perfect variation chart, continually brought down to the latest times, would materially assist in determining the longitude. Imagine, for example, that we found ourselves in a certain place on sea, or in an unknown region, we should first determine the variation of the compass, either by a meridian line or some other method already described (162), suppose the declination to be 5° East; this determined, we seek in the chart for the two lines under which the given declination is found,—we may then be fully assured of being under one or the other of these lines. If we now determine

our latitude, which is easily done, nothing remains but to mark on these two lines of 5° easterly variation, the two points of equal latitude; now the circumstances of the voyage would decide in which of these points we were placed, since they would necessarily be very far removed from each other; a means of determining the longitude by the variation of the needle, was in fact a main object of Halley's expedition.

248. Beside the great secular or progressive movement (244), the magnetic needle is found to exhibit a sensible change from month to month, from day to day, and even from hour to hour. This important fact of the daily variation of the needle was first announced in 1722 by Graham, a celebrated optician of London, who observed that whilst the needle was annually changing its direction, its north extremity advanced westward in the early part of the day, and returned again in the evening eastward to the same position. The amount of this daily variation amounted then to about half a degree. Since this time the fact has been completely investigated by very refined means of observation (163), and the following general results arrived at:— The north pole of the needle begins between 7 and 8 A.M. to move westward, and this movement continues until 1 P.M. About this time the needle becomes stationary, and soon begins to retrograde east, but with a slower motion than that of its previous advance. About 10 P.M. the needle is again stationary at the point from whence it started. A smaller second oscillation now ensues during the night; the north pole moves slowly west until 3 A.M. and then returns again as before. The mean daily changes in this country, as observed by Beaufoy, and lately by Dr. Lloyd, amount to about 9·4 of a degree. The action of the sun is undoubtedly the cause of this daily disturbance of the magnetic needle; we may hence expect it to vary in different latitudes both as to time and extent; we require, however, further observa-

tion for determining whether the daily variations have the same direction in points of westerly declination, as in points of easterly (245). In the southern hemisphere the direction of the daily oscillation is reversed, the north end of the needle here advances eastward and returns westward.*

The annual periodical variation of the needle was discovered by Cassini in 1786, who found that the North Pole, from the vernal equinox to the summer solstice, moved eastward, and again retrograded west during the next nine months. This last motion, however, he found to exceed the previous easterly deviation, and constituted the yearly secular change.

The direction of the horizontal needle is in no degree affected by its energy as a magnet, whether possessing a strong or weak magnetic power, still its direction and all the laws of its variation remain the same; at least so far as hitherto observed.

249. *Phenomena of the Inclined Needle.*—The series of magnetic phenomena of the earth's magnetism which next claim our attention, are those of the magnetic dip or the inclination (21). Mr. Robert Norman, a celebrated optician of London, about the year 1756, having accurately poised some small compass-bars before touching them with the magnet, found subsequently, that when rendered magnetic, they all lost their balance, and assumed a certain angular position in regard to the horizon, so much so that the fly or card attached to them (148), required a counterpoise: this most important discovery naturally excited very intense interest as materially affecting the mariner's compass, and led the discoverer to construct an instrument by which the full amount of this inclination could be correctly estimated, and which he found at that time in London, viz. in 1756, to be nearly 72°. We have already described the nature of this instrument termed the

* Macdonald, Phil. Trans. 1796.

dipping-needle (153); we have now to consider its practical application to the purposes of scientific discovery.

The attention of mariners having become directed to the inclination of the needle, and the fly or cards of the compass as adjusted in London being found to lose their horizontality by a change of latitude, it soon became apparent that the inclination was not everywhere the same, until, as already observed (240), it was finally found to be least in the equatorial and greatest in the polar regions of the earth. Following out Halley's comprehensive views of lines of equal variation, the next great step in the construction of magnetic charts was the addition of lines of equal inclination; these have been termed isoclinal lines, and portray the course of equal dip in all those parts of the world in which observations have been effected.

250. *The Magnetic Equator.*—In uniting in this way all the points in which the inclination vanishes, that is, all the points in which the dipping-needle (153) is horizontal, we trace in the equatorial regions of the earth the course of a most interesting and important circular line, which we may consider as the magnetic equator. This line, as hitherto determined, appears embarrassed by disturbances arising not only from almost unavoidable imperfections in magnetical instruments and the means of observation, but likewise from the presence of ferruginous and magnetic masses in certain portions of the earth itself. Sir James Ross observes of the island of Trinidad, "As a magnetic station our observations were here utterly valueless. Three dipping-needles, placed at only just sufficient distance to insure their not influencing each other, indicated as much as 3° difference of dip."* This appears also to have been the case at St. Helena, and all volcanic islands.

The magnetic equator, as hitherto traced from a large mass of observations by Cook, Bayly, Dalrymple, and other navigators, discussed by Biot, Morlet, and Hanstein, would

* Antarctic Voyage.

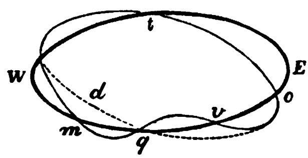


Fig. 123.

seem to be an irregular circular line crossing the terrestrial equator in at least three, if not four points. Thus, in the annexed Fig. 123, if we suppose the circle W *t* E to represent the terrestrial equator, then the irregular circular line *m t o* may be supposed to be the magnetic equator, evidently portraying between the points *w* and *o* either some great irregularity in the earth's magnetic condition, or the presence of some great disturbing force. From the great regularity in all the other portion of the curve, we can readily conceive its continued progress through the dotted line *d*, supposing the sources of disturbance we have adverted to not to exist. Duperry, who crossed the Magnetic Equator in the *Coquille* no less than six times during the French expedition of 1822 to 1825, and to whose indefatigable zeal and ability we are indebted for a most careful investigation of this great physical problem, has given, in the Annales de Chemie for 1830, a valuable magnetic chart, representing, according to his researches, its general course. Duperry traces this great magnetic curve, from his own observations alone, through an extent of 247° of west longitude, comprising the Atlantic Ocean, part of South America, the great Equinoctial Ocean, or Pacific Ocean, as far as the west side of the island of Borneo. After this he relies on the observations of Colonel Sabine at St. Thomas in 1822, and of Captain J. de Blosselville* in the *Chevrette*, made in 1827. Adopting the eastern node, as determined by Sabine, which he places in long. 3° 20′ East of the meridian of Paris, in the Atlantic Ocean, not far from the west coast of Africa, the points of no inclination pass through Africa, and ascend into the northern hemisphere, probably up to the

* This most accomplished French navigator has since perished in exploring the frigid regions of the Arctic circle.

fifteenth degree of north latitude, so far as the Red Sea; then, descending through the Indian Ocean, they cross the southern extremity of Hindostan, the isles of Malacca and the northern extremity of Borneo; then traversing the great Pacific, they cross the equator of the globe in a second point, in about lon. 176° East of Paris; so that, according to this course, the magnetic equator is inclined to the equator at an angle of between 14° and 15°, crossing it in two points, nearly diametrically opposite. It is not unworthy of remark, that four-fifths of this great circle traverses the vast seas of the equatorial regions. Although the curve is certainly tolerably regular throughout at least one-half its course; yet a large amount of observations for all that portion running through the Pacific from 112° to 270° of west longitude, tend to involve it in inexplicable windings, such as shown in Fig. 122. By a careful analysis of the observations, recorded at long intervals of time, the nodes or points of intersection of the magnetic and terrestrial equators have a slow westerly movement.

251. The isoclinal lines, or lines of equal dip, relative to all that portion of the magnetic equator, w *t o*, Fig. 123, which appears perfectly circular, are upon the equidistant parallels fairly regular, and the dip pretty constant for the same parallel at least up to 60° of magnetic latitude (237). These parallels comprise Europe, Africa, the Atlantic, and the eastern shores of America. Biot, by a refined analysis, has given a formula for the inclination, which appears to represent the phenomena of the dip in some parts of the earth, with a fair degree of precision. According to this formula, the inclination of the magnetic needle in any place is twice its magnetic latitude, a deduction first arrived at by Kraft, of St. Petersburgh. Thus the magnetic latitude of Quito, in Peru, being 6° 33′ 10″, the inclination should be 13° 6′ 20″, that is, double this angular quantity. Now Humboldt gives the dip at Quito, from observation, 13° 21′ 54″, which is a fair coincidence. Barlow, considering

the magnetic condition of the earth as approaching that of a soft iron ball (234), arrives at a similar deduction; according to his formula, "the tangent of the dip is double the tangent of the magnetic latitude." It is, however, very doubtful whether such formulæ can be satisfactorily applied to the whole terrestrial surface, more especially in the present imperfect state of these inquiries.

The following table exhibits the inclination of the magnetic needle as determined at a few remarkable places of the globe, within a comparatively recent date.

SOUTHERN HEMISPHERE.

Place ..	Charlotte Sound.	Cape of Good Hope.	Lima.	Peru.	Alexandria.
Dip......	54° 50′	34°	10° 30′	0° 0′	31° 12′

NORTHERN HEMISPHERE.

Place ..	Rome.	Paris.	London.	Petersburgh.	Hudson's Bay.
Dip	60°	67°	69°	71°	89° 57′

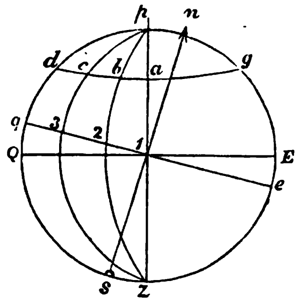
It is evident from this table that the magnetic inclination increases as we approach the polar regions (240).

The isoclinal lines appear to form irregular oval curves, diminishing in magnitude in each hemisphere as they recede from the magnetic equator.

252. Were the mass of the earth regularly magnetic, having its axis and poles of revolution at a given angle with the magnetic axis, we might possibly in this case derive from the dipping-needle a means of determining the longitude, for the parallels of magnetic latitude (237) would then cut the parallels of geographical latitude and meridians of longitude obliquely; hence all the points of longitude, in the same parallel of terrestrial latitude, would give a different dip; as being at different distances from the magnetic equator (248). Let, for example, *p z*, Fig. 124, be the axis of revolution, and *s n* the magnetic axis. Let E Q be the terrestrial,

and *e q* the magnetic equator; take any geographical parallel *d a g*, and any given meridians of longitude, *a*, *b*, *c*, *d*. Then, as is evident, the points of longitude, *a*, *b*, *c*, *d*, taken upon the same parallel, *d a g*, will be unequally distant from the magnetic equator *e q;* hence the inclination will be different in these points (248); that is to say, the latitude being known, the longitude would be a function of the magnetic dip, and would increase or decrease with the distance of the given point from the magnetic equator; although the imperfect state of our knowledge of terrestrial magnetism does not admit of a practical application of this method, it may still prove valuable in some particular cases, and is very worthy of further consideration.

Fig. 124.



253. The magnetic dip, like the direction of the horizontal needle (242), is subject to continual and progressive changes, both secular and periodical, and is at this present moment rapidly decreasing. According to the records handed down to us by different observers in the pages of the Phil. Transactions, the inclination at London in 1576 was 71° 50′. In 1676 it had become 73° 30′. In 1723 it was 74° 42′, having here reached a maximum. In 1790 it had decreased to 71° 53′. In 1800 to 70° 35′. In 1821 the magnetic dip, as determined by Sabine, was 70° 3′. In 1830 Captain Kater gives it as 69° 38′. According to the observations made at the Royal Observatory, Greenwich, it is now about 68° 30′; having decreased about 6° 12′ in 128 years, or at the rate of about 3′ each year nearly. If the early observations are to be relied on, the magnetic dip, when first observed by Norman in 1576, was increasing, and had attained a maximum in 1723, having increased about 2½° in 147

years; being at the rate of about $1\frac{1}{4}'$ annually. Since this it has continually decreased, and with increasing rapidity. The mean annual movement from 1830 to 1850 being at the rate of more than $4'$ each year, whilst the first annual decrease between 1723 and 1790 was only at the rate of about $2{\cdot}5'$ annually. Admitting some sources of error in the earlier observations, there is still sufficient evidence of an accelerated and retarded movement in the secular changes of the inclined needle.

The inclination like the declination appears subject also to a slight hourly variation; it is, however, very small. According to Hanstein, the inclination is about $4'$ greater in the morning than in the afternoon.

The inclined needle, like the horizontal needle, is not affected by its power as a magnet as to direction; whatever be the magnetic force, the angle of inclination remains the same under the same circumstances.

254. *Needle of Oscillation, or Magnetic Pendulum.*—Although the phenomena of the variation and inclination of the magnetic needle pourtray, under two peculiar forms, the general distribution of magnetism throughout the earth considered as a magnetic body, yet these forms are not so well adapted to convey so definite a view of the magnetism of our planet as would be obtained by an adequate examination of the relative magnetic intensity of different points of its surface. A large number of facts have been adduced to show that a freely-suspended needle in a state of oscillation is influenced by the magnetic force of the earth in a way analogous to that of a common pendulum oscillating by the influence of gravity; and that hence, by means of such a needle (138), we may determine the ratio of the intensity of terrestrial magnetic force throughout the whole extent of the earth's surface. This method of determining the magnetic intensity in the different regions of our globe was first suggested by Graham, so long since as the year 1775, and was afterwards more fully employed and perfected by Cou-

lombe, Humboldt, and Hanstein. The examination of the earth's magnetic intensity had also, at the instigation of the Royal Academy of Sciences, engaged the attention of the unfortunate La Perouse, in his expedition to the South Sea in 1785. The results, however, if any, perished with the expedition.

The nature and principle of the instrument more especially adapted as a magnetic pendulum has been already described and explained (139); and we have seen that the force urging the needle is taken as proportional to the square of the number of vibrations made in a given time. It is, however, essential to remember that, unlike the horizontal and inclined needles as to direction, this law applies as much to the magnetic force of the needle itself (141) as to the magnetic intensity of the earth, a condition which at once destroys the perfect analogy between a vibrating magnetic needle and a common pendulum, oscillating by the force of gravity. That would be the most perfect form of magnetic pendulum which would only involve in the consideration of the force in operation, the magnetic force of the earth itself, much in the same way as in measuring the force of gravity by the common pendulum we neglect the small attractive force of the matter of the pendulum, as being indefinitely small in comparison with the gravitating force of the earth. If a small needle of perfectly soft iron, not having any polarity of its own, and delicately suspended, could be caused to vibrate across the magnetic meridian at various parts of the earth, solely by the influence of terrestrial magnetic induction, we should then have a magnetic pendulum approaching the condition of the common pendulum; we cannot, however, produce such a result, and we therefore have recourse to needles of tempered steel, permanently magnetic; that is to say, we give our pendulum an inherent force, so as to put it in a position to operate upon the magnetism of the earth; it still remains, therefore, to inquire what new corrections it

may be requisite to introduce into our calculation of the experimental results obtained under this peculiar condition of the vibrating body, more especially when we observe (221), that the magnetic force exerted between opposite and permanent magnetic polarities, may vary in a different way, from that between a magnet and soft iron (218), and hence the same law of force between the centre and poles of a magnetic bar (227, Exp. 57), is not found to obtain when the force is taken between the different points of the bar and a small suspended magnet. The true measure of the earth's magnetic intensity at any point of its surface would be its inductive force on soft-iron. This, according to the laws we have arrived at (214), would be as the quantity of magnetism in operation directly, and as the distance inversely. Supposing we could actually measure the reciprocal force between any point of the earth's surface, considered as a magnet, and a given mass of soft iron, without sensible polarity, then, as we have shown (229 and 230), the relative quantity of magnetism in operation as referred to the earth, is represented by the square roots of the respective intensities or force of the reciprocal attraction.

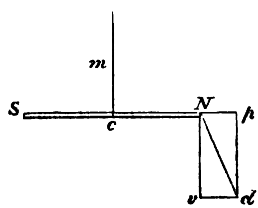
The method, however, commonly resorted to, of determining the magnetic intensity of any point of the terrestrial surface, is that of the vibrating magnetic bar (138) (254), as being upon the whole simple and available. It is, nevertheless, unquestionably open to objection, and the results hitherto arrived at by such means are not to be viewed in any other light than that of rough approximations. When we employ this method, we must take especial care to operate with the same needle, and with a needle in which the magnetism may be considered as invariable; to insure this, it is even found requisite to apply a small correction for changes of temperature.

255. In determining the terrestrial magnetic intensity with the needle of oscillation, we may either employ the

inclined needle (156), or the horizontal needle (142), or otherwise the vertical needle (156). From the circumstance, however, of the greater impediment to motion in the construction of the dipping-needle (153), the delicately-suspended horizontal needle (142) is commonly preferred; notwithstanding that it involves some final calculation before the total intensity can be determined.

Let, for example, S N, Fig. 125, be a light magnetic bar horizontally suspended by a fibre of silk *m* (142). Let N *d* be its natural inclination or dip at a certain point of the earth's surface; then taking this line N *d* to represent the total magnetic force,* we may conceive this force to be the equivalent or resultant of two other forces; one, N *p*, acting in the horizontal direction S N of the needle, and the other, N *v*, acting in the vertical or direction perpendicular to the line of the needle.* These two forces have been termed the horizontal and vertical components of the terrestrial magnetic force, such as it is found under any inclined or natural direction N *d*. If, therefore, we take the oscillations of the dipping-needle as a measure of the intensity, we may suppose the oscillations to result from the whole N *d* of the terrestrial magnetic force, since the needle vibrates across the line N *d*, or line of its natural direction; but if we take the oscillations of the horizontal needle as a measure of the intensity, then, as is evident, the vibrations do not result from the action of the whole of the terrestrial magnetic force N *d*, but only from that part of it, N *p*, acting in the horizontal line of the needle, and which will be greater or less according as the direction is more or less inclined to the horizon. Now it is easy to see in the above Fig. 125, that taking N *p* to represent the horizontal component of

Fig. 125.



* Rudimentary Mechanics. † See note (156).

the total force N d, we have N p = cos. of angle p N d (182); that is to say, the cosine of the dip. So that calling total force N d = R, and the horizontal force or component N $p = r$, we have r = R × cos. of dip, the cosine of the dip being the function of the obliquity which represents that portion of the whole force acting on the horizontal needle (196). We may arrive in a similar way at the total intensity by means of the vertical component N v, that is, by observing the oscillations of a vertical needle (156). In this case, however, we have to take into account the vertical force N $v = p\ d$ = sin. of the angle or dip p N d, which, calling the vertical force = S, gives S = R × sin. of the dip.* The first of these methods, however, is usually preferred; and from this we obtain $\text{R} = \dfrac{r}{\text{cos. of dip}}$.

256. We are indebted to the indefatigable Humboldt for the first practical results of the application of the needle of oscillation to the investigation of the variable magnetic intensity of the earth; having carefully determined the time of a given number of oscillations of a small magnetic needle at Paris, he transported the same needle to Peru, and again examined its rate of vibration; the result was, that whilst this needle performed at Paris 245 oscillations in ten minutes, it only made at Peru 211 oscillations in the same time. The relative intensities (139) therefore were as $245^2 : 211^2$, that is, as 1·3482 : 1; or, calling the intensity at Peru; a point of the magnetic equator; unity, then the force at Peru and Paris would be as 1 : 1·3482.† This kind of experiment has since been extended to almost every

* These formulæ will be more fully comprehended by referring to the notes in paragraphs 145, 183, and 196; see also p. 26.

† At the time when Humboldt made this experiment, an opinion prevailed that the intensity was the least where the dip was zero; it was on this account that Peru was taken as unity. Some doubts, however, have since arisen upon this point; still the scale assumed by Humboldt is usually resorted to; hence, to express intensities less than that of the magnetic equator, we must employ numbers less than unity.

known part of the globe; the result has been a series of numbers representing the ratio of the terrestrial magnetic intensity to a given unit for every point of the earth's surface. The following table may be taken as an illustration for a few remarkable places.

Place ..	A little W. of St. Hel.	Rio de Janeiro.	Cape of Good Hope.	Peru.	Isle of France.
Intensity	0·743	0·887	0·945	1	1·096

Place ..	Naples.	Paris.	Berlin.	London.	Baffin's Bay.
Intensity	1·274	1·348	1·350	1·369	1·707

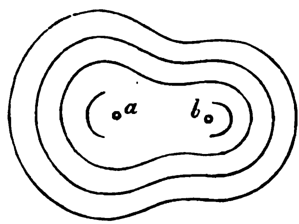
It appears by this table, as first announced by Humboldt, that the intensity is least about the equatorial regions of the globe, and greatest in the polar regions. By the indefatigable labours of Hanstein, Erman, and a few other observers, we are in possession of a table of intensities for a large portion of the terrestrial surface.

257. If we connect all those points in which the terrestrial magnetic intensity as thus deduced is the same, we arrive at a series of lines termed "Isodynamic," or lines of equal power. These lines, according to Sabine and others, are not always parallel to the isoclinal lines; the differences, moreover, are systematic. It has been further inferred, from a chart of these lines, that the points of greatest and least intensity are not identical with the points of greatest and least inclination; the intensity, therefore, of the magnetic equator may not be everywhere the same.

Although these isodynamic lines are still rough and incomplete, yet we cannot doubt of their being curves of double curvature returning into themselves. In Siberia and the Pacific toward the polar regions they are found, according to Hanstein and Erman, to consist of a system of double loops, as it were, enclosing two polar points. The

annexed Fig. 126 may be taken in the way of approximation to the form of these loops, in which *a b* are the points or poles of the system. Hanstein places the western of these intensity poles near Hudson's Bay, in lat. 50° N., lon. 90° W.; and the other eastern, or Siberian pole, in probably about 70° North latitude, and 120° East longitude. In the southern hemisphere, the loop form of the intensity lines and the two intensity poles are more fully developed as we recede from the equator. The two southern points have been placed, one to the south of New Holland, in lat. 60° South, lon. 140° East; the other, in the South Pacific Sea, also in lat. 60° South, but lon. 120° West. These four poles, therefore, are not diametrically opposite each other. The intensity of the North American pole and that of the southern pole, near New Holland, are nearly alike, being both about 1·8; as are also those of the Siberian and South Pacific poles, which are about 1·7. The two polar intensities, therefore, in each hemisphere, are of unequal force. Both the isoclinal and isodynamic lines would appear from these investigations to enclose two foci or points of greatest attraction, the bends or flexures of the curves being less marked as we approach the equator.

Fig. 126.



On comparing the observations of Sir James C. Ross with those of Erman, we find that the terrestrial magnetic force towards the south pole increases nearly in the ratio of 1 : 3. Since, upon a discussion of all the best observations, it appears that the maximum may be taken as 2·052, the minimum as 0·706; both these are found in the southern hemisphere. The ratio of the maximum to the minimum force then is as 1 : 2·9 nearly, or nearly as 1 : 3. From the profound inquiries of Gauss, it appears that the

total and absolute terrestrial magnetic force, considering the earth as a magnet, is equal to six magnetic steel bars of a pound weight, magnetized to saturation, for every cubic yard of surface. Compared with one such bar, the total magnetism of the earth is as 8,464,000,000,000,000,000,000 : 1, a most inconceivable proportion.

The terrestrial magnetic force as thus deduced by the needle of oscillation, like the elements of declination and dip, is subject both to secular and periodical changes (242). The amount of the secular change is not yet determined, according to Hanstein; however, the intensity is gradually declining throughout Europe. Sir James Clarke Ross, from observations on board the *Erebus* in 1839, concludes that the line of least intensity had advanced considerably northward.

The periodical and diurnal variation, as hitherto observed, gives a maximum of intensity between 9 and 10 P.M., and a minimum between 10 and 11 A.M. The monthly variation evinces a maximum in December and a minimum in June. The greatest change or difference in the annual intensity of the northern hemisphere is about 0·0359.

258. The needle of oscillation is not the only means employed for determining the magnetic intensity of the earth. Gauss resorts, for example, to a statical experiment, which consists in deflecting a magnet delicately suspended by a silk filament from its meridian, by means of a second magnet (134), and from which he conceives the absolute intensity may be derived.* Mr. Fox also proposes to determine the earth's intensity by means of weights applied on his dipping-needle deflector (160) to balance the dip.

Variations in intensity are measured by the bifilar and vertical force magnetometers (166) (168), as also by a species of steelyard balance contrived by Professor Lloyd.†

259. *Position of the Terrestrial Magnetic Poles.*—The

* See Gauss, Intensitas vis Magneticæ Terrestris, &c.

† Account of the Dublin Magnetic Observatory.

first step in the generalization of the phenomena of the declination of the magnetic needle is due to Halley, who conceived the notion of four terrestrial magnetic poles, two in each hemisphere, one fixed, the other in motion. The north pole, nearest to England, he places in lat. 83° North, longitude about 5° West of Greenwich; the other in lat. 75° North, lon. 115° West. The two southern poles he places, one in latitude about 74° South, lon. 95° West; the other in about 70° South lat., and lon. 120° East. These positions he thinks consistent with the then observed direction of the magnetic needle in various places. Churchman, in his "Magnetic Atlas," only traces two poles, one in lat. 58° North, lon. 134° West; the other in lat. 58° South, lon. 165° East. Hanstein, from his magnetic chart of variation, dip, and intensity (246), is led with Halley to infer the existence of two poles of unequal power in each hemisphere, toward which the isogonal lines appear to converge by two separate systems in each hemisphere. The stronger north pole he finds above the American continent, in lat. 70° North, lon. 92° West; the weaker he places in the Arctic Ocean, in lat. 85° North, lon. 140° E. The stronger south pole he places in lat. 69° South, lon. 132° E., not far south-west of Van Diemen's Land; the weaker south pole is in lat. 79° South, lon. 136° West, being south-west of Terra del Fuego. These four poles, therefore, are at present nearly diametrically opposite; their precise position, however, is subject to a great secular change. Did we infer the position of the magnetic poles from the course of the magnetic equator, considering them as the extremities of the axis of this great circle, we should find the north magnetic pole in Greenland, a little beyond Baffin's Bay, lat. 78°, lon. 60° West; and the south magnetic pole in the Antarctic Sea, lat. 76° South, lon. 130° East. The precise position and course of the magnetic equator, however, are still involved in doubt; which, together with the apparently uncertain and irregular distribution of the earth's magnetism, forbids our

placing any great confidence in the position of the two magnetic poles, as thus deduced.

By observations with the dipping-needle on board H.M. ship *Brazen*, in May, 1813, a point approaching verticity was found in Hudson's Bay, in lat. 69°, lon. 92° West. Parry, in August, 1819, was to the north of this, and found the dip 88° 37′. The position of the pole, from his subsequent observations, would be in about lat. 71°, lon. 93° West. In 1832, the observations of Sir James C. Ross completely confirmed the close approximative position of this point of polarity. This celebrated navigator found the dip near Prince Regent's Inlet, in the great American continent, lat. 70° North, lon. 96° West, to be within one minute of 90°, and which coincides wonderfully with Hanstein's deduction. Barlow also observes, "This is precisely the point in my globe and chart in which, by supposing all the lines to meet, the several curves would best preserve their unity of character as a system." So far, therefore, we have confirmed by observation the position of at least one point of verticity of the dipping-needle in the northern hemisphere. Gauss, whose enlarged, profound, and comprehensive views of terrestrial magnetism have so long commanded the attention of European science, has endeavoured, from certain theoretical considerations, to doubt the existence of more than a single pole in each hemisphere, one of which he places in about lat. 73° 35′ North, lon. 95° West; the other in about lat. 72° 30′ South, lon. 152° East. Both these points are not far from the results of observation.

Professor Barlow, following out his formula for the dip, viz., tangent $\delta = 2$ tangent λ (251), and, considering the magnetic condition of the earth as being analogous to that of a simple iron ball or shell (234), is led to conclude that each point of the terrestrial surface has its own particular polarizing axis, the extremities of which fall probably in all cases within the polar circles. These are the least limits we can at present assign them. There is consequently, he

says, no particular spot in the polar regions, which may, *par excellence*, be taken as the magnetic pole; if there were, he imagines it might, by the above formula, be easily computed, whereas, on subjecting the observed elements to calculations, he found discrepancies of no less than 10° of latitude, and 55° of longitude. Observation, however, still confirms the notion of a point of verticity for the dipping-needle.

260. *Magnetic Storms.*—Besides the secular and periodical variations of the magnetism of the earth, as indicated by the phenomena of the horizontal and inclined needles, we also find these needles subject to certain irregular variations, uncontrolled by any apparent law. It is to the illustrious and indefatigable Humboldt, that we owe all our first knowledge of such perturbations. Being engaged at Berlin in 1806 and 1807, in examining the changes in the declination of the needle for every half-hour, his attention was called to certain capricious agitations in its position, not referable to any accidental or mechanical cause, and which occasionally caused so great an oscillation as to lead him to refer them to a sort of magnetic reaction, propagated from the interior of the earth. He accordingly designates these disturbances as "magnetic storms," as being analogous to the sudden changes of electric tension which ensue in the electric storms of the atmosphere. During these storms the needle is observed to be affected by a sort of shivering motion, and to oscillate several degrees on each side of its mean position. In 1818, further observations were made simultaneously by Arago, at Paris, and Kupffer, at Kassan, in Russia, which showed, in a satisfactory way, that these perturbations, announced by Humboldt, occurred in both places at the same instant of time, notwithstanding that the places of observation were separated by 47° of longitude. Full attention being at length called to this subject, Humboldt, in 1830, succeeded in establishing magnetic observatories in various parts of Russia, which have since been extended to other

parts of the world (169), constituting such a network of inquiry into all the great facts of terrestrial magnetism as would have been but a few years before difficult to imagine. Since the year 1828, from Toronto, in Upper Canada, to the Cape of Good Hope and Van Diemen's Land, from Paris to Pekin, we find magnetic observatories, all established under one uniform system, and carrying on similar and simultaneous observations. The principal magnetic instruments employed in these observatories have been already described (162), and from continuous observations, carefully registered, in almost every country of the globe, we are presented with the startling fact of an unceasing series of what may be termed terrestrial magnetic pulsations, extending simultaneously over an interval equal at least to the whole breadth of Europe, and perhaps over the whole terrestrial surface. "When," says Humboldt, "the tranquil hourly motion of the needle is disturbed by a magnetic storm, the perturbation frequently proclaims itself over hundreds and thousands of miles simultaneously, or is propagated gradually in brief intervals of time in every direction over the surface of the earth."*

261. Beside these magnetic disturbances referable to some hidden and sudden change in the condition of the earth's magnetism, we find other singular disturbances in the position of the magnetic needle at the instant of the appearance of the Aurora Borealis, or Northern Lights. This fact was especially noticed and studied by Dalton so long since as the year 1793, who observed that the luminous beams were parallel to the dip, and the arches at right angles to the magnetic meridian. This disturbance of the magnetic needle consists in an irregular oscillation sometimes to the eastward, and then to the westward of its mean direction. The greatest amount of disturbance is when the Aurora is in the zenith. Hanstein also, who has studied this phenomenon, says that the shivering movements of the needle

* Cosmos.

never perhaps occur except at the time of an Aurora, and that the disturbances are felt at the same instant of time in places widely separated; the extent of the movement may, in twenty-four hours, amount to between 5° and 6°. This disturbance of the magnetic needle is equally wonderful and important in its character as the former, and may possibly be found to be identical with it. Arago thinks that the Aurora disturbs the needle even before the light shows itself in the horizon. The Auroras which are only visible in America and Siberia are, he says, found to affect the magnetic needle at Paris. It is not improbable that the presence of an Aurora and the disturbance of the magnetic needle are both effects of the same or a similar cause, so that we cannot assume the presence of the Aurora as the active force; we should rather regard it as an accompanying phenomenon; more especially as we find, according to Capt. Foster's observations at Port Bowen, that, during certain Auroras, the magnetic needle remains undisturbed. It has been further shown experimentally, by the author of this work (Edinb. Phil. Trans. 1834, vol. xiii.), that the magnetic oscillations are unaffected by the presence of a powerful column of mere electrical light flashing through an exhausted receiver 6 feet high and 4 inches in diameter.

Halley, more than a century since, considered the Aurora to be a magnetic phenomenon, a conjecture which bids fair to receive complete confirmation. According to Humboldt, the Aurora may be considered as a terrestrial magnetic activity raised to the intensity of a luminous phenomenon, one of the sides of which is the light, the other the disturbance of the needle; so that this magnificent appearance may be considered as the act of discharge at the conclusion of a magnetic storm.

VIII.

REVIEW OF MAGNETIC THEORY.

General Principles—First Views of Terrestrial Magnetism—Hypothesis of Halley—Speculations of Euler—Theoretical Speculations of Hanstein—Grover's Magnetic Orbit—Theory of Barlow—Hypothesis of Biot—Theory of Gauss—Electro-Magnetic Theory—Theoretical Views and recent Discoveries of Faraday—Theory of Ordinary Magnetic Action.

262. One of the great objects of physical science is to trace the relations and determine the laws of sequence in any observed series of natural phenomena, the study of nature being "the study of facts, not of causes;" it is this which characterizes the learning of the great founder of the inductive philosophy, and which essentially separates it from the conjectural philosophy of remote ages, the object of which was the study of causes rather than of facts. By the term theory, as applied in modern science, we are to understand an intelligibly connected body of facts, all referable to one or more general principles. With respect to the hidden or efficient cause of the phenomena observed, we have really no substantial knowledge of it whatever. That all bodies tend to the centre of the earth, and masses of matter toward each other, are universal facts, and upon these is based the whole theory of gravitation, and a lucid explanation of the system of the world. In the midst of this knowledge, however, we are most profoundly ignorant of the nature of the agency by which matter gravitates; and to speculate concerning it through the instrumentality of fiction, would be only to wander in a labyrinth of conjecture. What we call an explanation of observed phenomena, is a clear apprehension of all the dependencies in a great

chain of sequence. Take, for example, the question of the rise of water in a pump before the discovery of Toricelli; here we had two facts before us: the elevation of the fluid full thirty feet above its level, and the production of empty space by the motion of the piston of the pump, still the vacuum and the rise of the fluid had no apparent dependence on each other. The assumption by the ancient philosophers that the elevation of the fluid arose from the circumstance that nature abhorred a vacuum, was, in fact, no adequate intermediate link; it explained nothing. Directly, however, it was proved by the experiment of Toricelli that the atmosphere pressed upon bodies with a force equal to at least 14 lbs. on the square inch, then the cause of the rise of the fluid was instantly apparent, and the phenomena were explained. In the construction, therefore, of any theory, it is essential that the basis of it be some principle reducible to a fact; and, next, that the fact be universal; that is, without exception. Directly we refer the phenomena to any fictitious principle not reducible to a fact, we have no longer a theory; we have only at the best a conjectural hypothesis; in short, we substitute something which has no demonstrable existence for that which may be: in this case, we only require that what we assume is possible. An hypothesis of this kind is still not without its uses; and it is theoretically admissible so long as it runs parallel with the facts observed.

Magnetic theory, embarrassed by the complicated and mysterious character of the attendant phenomena, has hitherto made but comparatively little progress toward perfection; so that we are unable, as in gravitation, to refer the facts to one ultimate and universal elementary principle; hence almost every speculation relative to the phenomena of magnetism partakes more or less of the nature of an hypothetical assumption not based on any recognized fact.

263. *First Views of Terrestrial Magnetism.*—The philoso-

phers of the sixteenth century, not having any definite notion of the phenomena of the compass-needle, conceived it to be influenced by some mysterious point of force, existing in the regions of space. Descartes and others conceived it to be under the dominion of vast magnetic rocks. The discovery of the magnetic inclination (249) by Norman, in 1580, however, clearly proved that the cause of the directive position of the magnetic needle was to be sought for in the general mass of the earth; whilst Gilbert, in 1590, taking a bolder view of this great physical question, conceived the terrestrial sphere to be in itself a vast magnet, endowed with a permanent polarity, and hence approaching the general condition of an ordinary loadstone. Gilbert supposed, however, that the solid parts only of the earth were magnetic, not the water or other fluids; hence arose changes in the direction of the needle, which, whilst it assumed a given position, in obedience to the laws of common magnets (14), would at the same time be more or less drawn toward the land, and be influenced by it in various ways.

Bond, in 1673, endeavoured to calculate and explain the phenomena of the magnetic needle, on the hypothesis of the earth being a great magnet, and assumed the existence of two terrestrial magnetic poles, and a magnetic axis inclined to the axis of rotation, and passing through the centre of the earth; hence the magnetic poles and the true poles could not on this hypothesis coincide. With a view of explaining the great secular changes in the declination, the magnetic poles were supposed to have a slow movement of revolution about the poles of the earth.

264. *Hypothesis of Halley.*—It is to the celebrated Halley that we owe the first great attempt to bring the complex phenomena of the horizontal needle under the dominion of a more comprehensive theory, which, although it may appear at first to be of a somewhat rude and improbable character, still affords a fair field for the application of exact reasoning, and a means of comparing facts; indeed it

is but justice to this truly great man to observe, that he never pretended to more than an attempt to throw some light upon "the abstruse mystery of the variation," and lead philosophers to apply themselves more forcibly to so important a subject. Were the variation always relative to two fixed points or poles, near the poles of rotation, the magnetic axis passing through the centre of the earth; then it should be always the same for each place, and the lines of no variation would be meridian lines, passing through the magnetic and real poles of the earth; but the lines of no variation are not meridian lines, but curves of a somewhat inexplicable course (245). Halley, therefore, foreseeing this difficulty, assumed the existence of at least four poles, to which the variation had reference, two in the northern and two in the southern hemisphere; but since the observed phenomena evidently indicate a constant change of place in the relative position of these poles, he further supposes that the whole "magnetical system of the globe has one or perhaps more motions, the effects of which extend from pole to pole." To render this magnetical movement intelligible, he supposes a great portion of the interior of the earth to move within the external crust; and to admit of this motion, he imagines this interior portion to be detached and separated from the surface by an intervening fluid medium, so that, according to this, the terrestrial mass is a sort of double loadstone, consisting of an interior magnetic, spherical nucleus, surrounded by an external and spherical magnetic shell, the magnetic axis of each passing through the centre of the whole globe of the earth, the nucleus is supposed to have its centre of gravity fixed in the common centre of the general spherical mass, and to partake of the diurnal rotation about the same axis. By further supposing that the rotatory movement of the surface or external shell is rather more rapid than that of the interior globe, by some extremely small quantity, then, as is evident, the poles of the interior magnet will be continually shifting their places in respect

of the poles of the outer magnetic shell, being at every revolution left as it were a little in the rear, and consequently moving apparently westward. Halley supposes the difference of velocity to be so extremely little as to be scarcely appreciable upon 365 revolutions, and only to assume a sensible form by the operation of a great period of time. Under this condition, then, if we conceive the exterior shell to be a magnet, having its poles fixed, and at a given distance from the poles of rotation; and if the internal globe be also a magnet, having its poles fixed in two other places, distant also from the axis of rotation; and that these last poles are continually shifting their places in respect of the exterior poles, we may then, he thinks, give a reasonable account of the four magnetic poles of the earth, considered as a magnet, and the several phenomena of the variation of the horizontal needle. By the gradual translation of the poles of the internal globe, the direction of the needle is variously influenced, according to the directive power of each pole; hence there will be a period of revolution, after which the variations will return again as before. If they should not, then it may be inferred that there exist internal spherical shells, having a common nucleus, and consequently producing more magnetic poles, all these concentric magnetic spheres being separated by fluid media; and this he thinks a possible constitution of the interior of our planet, which, for anything we know to the contrary, may, through the operation of the fluid media, be a source of existence to organized beings. In this hypothesis all those parts of the earth nearest either of the poles will for the time be governed more or less by the influence of that pole; thus, taking the nearest pole to Britain as being in the meridian of the Land's End, and about 7° from the true north pole, this pole will govern Europe, Tartary, and the North Sea. All places to the east of this meridian will have a westerly variation; all places west of it a westerly variation, until we approach the influence of the other pole,

in North America, supposed to be on the meridian of California. The separate and combined influences of all the four poles in different zones of the earth produce the great differences observed in the variation of the needle.

This hypothesis of Halley, although far within the region of mere conjecture, and not at first view sanctioned by any high degree of probability, must still be considered as a valuable step in the progress of magnetic theory, and well calculated as a stepping-stone to more perfect views of the magnetism of the earth.

265. *Speculations of Euler.*—Euler, who investigated this subject in 1757, with his accustomed ability, does not think, in considering the earth as a magnet, that it is requisite to assume the existence of more than two magnetic poles, provided their just place be assigned. According to his view, we have yet to consider the case of two magnetic poles not precisely opposite each other, or, which comes to the same thing, in which the magnetic axis does not pass through the centre of the earth. Now, in this case, Euler endeavours to show that the lines of no declination may actually assume a direction similar to that which, from observation, we find they do assume; and that it is even possible to assign to the two poles such proportions as to produce lines of variation similar to those isogonal lines, which at first appear so unaccountable. Having fixed the two poles, the determination of the direction of these lines becomes a problem in geometry.

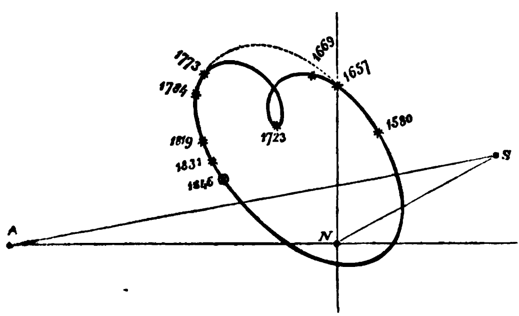
266. *Theory of Hanstein.*—Theoretical views of terrestrial magnetism do not appear to have greatly advanced beyond the condition in which Halley left them until 1811, when the Royal Danish Academy proposed the variation of the needle as a prize question; then it was that M. Hanstein undertook a re-examination of the whole subject, with a view to determine whether two magnetic poles, revolving round the pole of the earth in indefinite periods as maintained by Euler, would explain the phenomena; or whether four poles,

as assigned by Halley, were requisite; or, finally, whether the motion of magnetic polar points, about the poles of the earth, be in any way competent to represent the observed phenomena at all. We have already adverted to the extraordinary and elaborate magnetic charts of this unwearied philosopher, with their marked systems of isogonal lines, loops, ovals, and other intricate convolutions, and which it would seem are all sweeping westward, each in separate progression, and each assuming some new modification of flexure. So completely has the question been worked out, that by means of these charts we obtain a faint glimpse of the progressive state of magnetic declination for two centuries, viz. from 1600 to 1800. The results of the investigation confirm, according to Hanstein, the existence of four poles, as imagined by Halley. These four poles, however, are of unequal force, and are all supposed to be continually shifting their places; each has a separate independent movement and period. The present places of these poles, as assigned by Hanstein, we have already given (259); they are all supposed to have a regular oblique-circular motion about the poles of the earth,—the two north poles from West to East; the two south poles from East to West; and in the following periods:—The strongest north pole in 1,740 years; the weaker in 860 years: the strongest south pole in 4,609 years; the weaker in 1,304 years. Upon these data he assigns the position of these poles for the last half-century.*

* By a curious coincidence, these periods involve a number, 432, sacred with the Indians, Babylonians, Greeks, and Egyptians, as being dependent on great combinations of natural events; thus the periods 860, 1,304, 1,740, and 4,609, become by a slight modification 864, 1,296, 1,728, 4,320, which are not inadmissible, considering the complicated nature of the observations from which the first numbers are derived. Now these numbers are each equal to 432 multiplied by 2, 3, 4, and 10 successively. According to the Brahmin mythology, the world is divided into four periods, the first being 432,000 years, the second, 2 × 432,000, the third 3 × 432,000, the fourth, 10 × 432,000 years. It is also, according to Han-

267. *Grover's Magnetic Orbit.*—Much valuable information relative to this interesting speculation has been afforded by Grover.* By a careful and laborious examination of authentic observations, he endeavours to show that "the movement of the magnetic pole governing Europe is capable of recognition, that it possesses an orbitual character of which the general features can be distinctly traced." An horizontal action upon the needle is also inferred from these observations, depending on the isodynamic poles (257), by which he endeavours to explain the configuration of the isogonic lines. The magnetic orbit, as traced from observations on the magnetic needle in London, Paris, and St. Petersburgh, appears to be of the form given in the annexed Fig. 127. In this figure N is the true north pole in the

Fig. 127.



middle of a section of the northern hemisphere, and the

stein not unworthy of remark, that the sun's mean distance from the earth is 432 half radii of the sun ; the moon's mean distance, 432 half radii of the moon ; but what is more especially striking is the circumstance, that the number 25,920 = 432 x 60, is the smallest number, divisible at once by all the four periods, and hence the shortest time in which the four poles can accomplish a cycle. Now this time coincides exactly with the period in which the precessions of the equinoxes complete their circle, certainly a curious and remarkable series of coincidences.

* Observations on the Magnetic Orbit ; by the Rev. H. Grover. London : J. Weale, 1850.

L 2

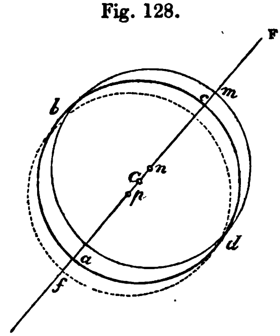
irregular elliptical curve, the path of the pole so far as hitherto observed. In this curve the author has localized eight assigned positions for the magnetic pole, from observations between the years 1580 and 1846. The points A and S represent the positions of the isodynamic poles, or points to which the isodynamic lines converge, one in Siberia, the other in America, and supposed to influence the position of the needle. In tracing the elements out of which this orbit is constructed, peculiarities present themselves, which throw much light on the whole magnetic system; for example, a certain acceleration and retardation of the motion, and the opposite bias of the two isodynamic hemispheres. By means of a critical examination of all the phenomena of this determined orbit, the author deduces some very general and curious facts bearing on the development of the magnetic lines, with their ovals, loops, and apparently inexplicable curvatures. The ovals he considers as temporary creations arising out of the peculiar position of the moving magnetic pole in relation to the two isodynamic poles A S, by which a bias is given to the needles of a whole district.

268. *Theory of Barlow.*—Professor Barlow, following up the construction of more perfect magnetic charts, is led to conclude that these charts present such a configuration of the magnetic lines as cannot be referred to any possible position of four or more magnetic poles; but conceives that each place has its own relative pole and polar revolution governed by some unkown cause. This theory is so general, that it must be conceived to set aside altogether the idea of any particular pole or point toward which the magnetic needle becomes directed, and consequently all idea of a single magnetic axis; it hence leaves the law of the changes in the direction of the needle undetermined. The fundamental principle, on which this theory rests, assumes the magnetic condition of the earth to be of that peculiar form observed in the passive or temporary magnetic state of a

soft iron ball or shell, and in which the poles or centres of action are always coincident with the centre of attraction of the surface, which is not the case in permanently-magnetized bodies. In these the centres of attraction are always at their poles. Professor Barlow having, as we have already seen (239), found the entire effect of a soft iron globe or shell to reside near the surface, proceeded to investigate a formula for representing the influence of these bodies on the compass-needle placed about them in different positions. Assuming upon the generally received hypothesis (14), that magnetic phenomena depend on two opposite fluids or forces, repulsive of themselves, but attractive of each other, and commonly existing in a greater or less degree of combination, we may suppose the action of the earth on spheres of soft iron, to take place on every particle of the mass in isoclinal lines (249) parallel to each other (102), and may further suppose that every particle of the iron is at the same distance from the centre of force as referred to the mass of the earth; in which case we may consider the effect upon each particle to be the same.

As this question is important in a theoretical view, we will take Professor Barlow's illustration of this probable magnetic condition of a soft iron ball or shell. Let *a b c d*, Fig. 128, be a neutral soft iron sphere; suppose F C *f* to be the direction of the dipping-needle, and F the centre of terrestrial magnetic force at an indefinite distance, then by the operation of this force upon each particle, in the way just stated, the two magnetic fluids or forces, resident in a combined state in the shell or globe *a b c d*, become separated, and may be supposed to form two spherical layers:

Fig. 128.



one *f b d*, whose centre is *p*; and another *m b d*, whose centre is *n*; the distance of these centres *p n* from each other depending on the susceptibility of the iron and other contingencies. In computing the action of an iron sphere in this state upon a distant magnetic particle, we may refer the action to those two centres *p n*, according to any assumed law of force (175). Professor Barlow supposes the force to be in the inverse duplicate ratio of the distance. This view differs from others of a similar kind in this, that the action or displacement of the fluids is referred to each particle, instead of the fluids being separated and accumulated in distinct poles; and also in the great fact that the displacement is confined to the surfaee, and not, as Coulombe supposed, referable to the mass. The centres of action *p n*, therefore, may become indefinitely near each other in the common centre of attraction of the surface, which is coincident with the centre of attraction of the mass only in spherical bodies, but on no others. Now by referring the earth's magnetism to an existing magnetic condition such as this, Professor Barlow finds that he is enabled to apply the analytical expressions, he had previously deduced for representing the influence of an iron sphere on the compass (238), to the phenomena of terrestrial magnetism; his general deductions being that the earth is not a permanent magnet, but owes its magnetic state entirely to induction; and that its action may be referred to two poles indefinitely near each other in the common centre of attraction of the surface; that is also of the mass of the earth. The latent magnetism of the sphere has in this case a mere condition of polarity. From whence this induction proceeds he does not pretend to determine. The illustrious Gableo had an idea that a magnetic agency existed in some points of space, which led him to ascribe the parallel direction of the earth's axis to a magnetic point of attraction in the distant heavens.

269. *Hypothesis of Biot.*—Biot, so long since as the year

1805, not finding it possible to reconcile observations on the variation and dip of the needle with the existence of two poles or centres of force near the terrestrial surface, thought of treating this problem under the condition that those centres were indeterminate, and then by a comparison of the general analytical result with further observations, endeavour to arrive at the precise position of these poles. Now it is not unworthy of remark, as being very confirmatory of Barlow's views, that the nearer the poles were taken toward each other, the nearer the computed and observed results were found to agree; until, at length, by taking them indefinitely near each other in the centre of the earth, the computed and observed results in many cases completely coincided. In this investigation Mons. Biot assumes two points in a given terrestrial magnetic axis, by one of which the needle is attracted, by the other repelled; and then investigates a formula for representing the dip and declination of the magnetic needle in any part of the earth in terms of an indeterminate distance between these points.

270. *Theory of Gauss.*—This accomplished philosopher, whose magnetic researches have become in recent periods the wonder and admiration of Europe, assumes the terrestrial magnetic force to be the collective effect of the magnetism of the mass, and is led to consider the term pole as a very arbitrary assumption; no number of definite points, be they 2 or 4, or even more, will explain the phenomena according to the laws of common magnetism. In the most simple meaning of the term pole, Gauss considers that there are only two, one in each hemisphere. If there were four, we should have necessarily three points of verticity in each hemisphere; that is to say, there would be a point between each two poles in which the needle would not obey the action of either exclusively, and would, consequently, be vertical; but such is not found to be the case. Gauss, starting from a great general principle, that mag-

netism is distributed through the mass of the earth in an unknown manner, has succeeded in obtaining, partly by theory and partly by adaptation, a sort of empirical formula which represents in a wonderful way the many complicated phenomena of the magnetic lines, and has so far embodied our knowledge of these phenomena in a law mathematically expressed. Gauss's investigation depends on the development of a peculiar function much employed in Physical Astronomy, and which is obtained by summing all the attractive and repulsive elements, each molecule being divided by its distance from the attracting or repelling point; what are termed the differential coefficients of this function express the resolved components of the total magnetic action (255). By this process it is demonstrated that whatever be the law of magnetic distribution, the dip, horizontal direction, and intensity at any place on the earth may be computed. Having exhibited his resulting formula in converging series, Gauss determines the declination, inclination, and intensity for ninety-one places on the earth's surface, and which are found to coincide with observation: one great feature, therefore, in this theory of terrestrial magnetism is, that the earth does not contain a single definite magnet, but irregularly-diffused magnetic elements, having collectively a distant resemblance to the condition of a common magnet. So that for magnetic poles we must substitute magnetic regions, over which a general magnetic influence obtains. Thus, instead of a Siberian pole, as determined by Hanstein, we have a Siberian region, in which the isogonal lines may be conceived to converge without coming absolutely to a point.

271. *Electro-Magnetic Theory.*—The solution of the problem, from whence the mass of the earth derives its magnetic state, is not in any way approached with so high a degree of probability as by the theory of electro-magnetic currents, caused to traverse the earth's surface by some of those natural agencies so continually operating on it. We

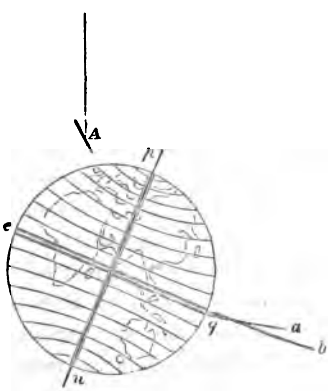
have seen (68), that by heating one extremity of a metallic bar or rod, the opposite extremity being kept cool, so as to produce a disturbed equilibrium of temperature, electro-magnetic currents are produced, of such force as to turn the compass needle at a large angle to its meridian. Sir David Brewster, so long since as the year 1821, observed a remarkable coincidence between the isothermal lines, or lines of equal heat, laid down by Humboldt, and the isogonal lines of Halley, and had deduced for our northern hemisphere two poles of greatest cold; both in the locality of Hanstein's magnetic poles, viz., an American pole, lat. 73° North, lon. 102° West; and an Asiatic pole, lat. 73° North, and lon. 78° East. Sir David Brewster* is led to conclude that two meridians of greatest heat, and two of greatest cold, are called into play, and was finally led to imagine that the magnetism of our globe depended in great measure on electro-, or rather thermo-magnetic currents. Taking into consideration the heated belt of the equatorial regions, and the mass of the polar ices on either side of it, we have, as observed by Dr. Traill, all the conditions of a vast thermo-magnetic machine. A great link in the chain, however, is still wanting; it is very difficult to say how or in what way these currents are caused to circulate about the mass of the earth. Grover, in his interesting little work on the magnetic orbit, already alluded to, has some interesting observations on this question. According to his view, the atmosphere is the immediate source of terrestrial magnetism, which contains within it isolated columns of conducting media; these surround the earth, and in such way, that in 365 revolutions the sun generates in it an electro-magnetic circulation; thus the terrestrial surface becomes enveloped in a vast electro-magnetic spiral coil (51), and we who live on it become placed intermediate between the coil and the surface by those peculiar motions of the earth which arise from the yearly cycle finding its period at different hours of the day,

* Edin. Phil. Trans. vol. ix.

and on different meridians; such a change may take place in the precise position of this great atmospheric coil from time to time as would correspond with the orbit of the magnetic revolution (267). The phenomena of periodical variations depend evidently on the action of heat and the position of the sun, and probably on resulting thermo-magnetic currents. Beyond this mere assumption, however, we have not any very secure basis for reasoning; the most admissible view of this kind of action, however, is the following:—During the diurnal motion of the earth, its surface, especially about the tropics, is continually heated and cooled in successive points, and in an east and west direction: if we admit, as in Exp. 50 (68), that thermo-magnetic currents become from this cause excited, and circulate in an east and west direction over the terrestrial surface, the result will be a magnetic development in direction north and south (48); hence there will be a magnetic development in the earth in a direction nearly parallel with its axis.

272. *Barlow's Electro-Magnetic Globe.*—From no one has the preceding electro-magnetic theory received so much substantial and fine experimental support as from the profound and great philosophical ingenuity of Professor Barlow. A hollow globe of wood, *p n*, Fig. 129, sixteen inches in diameter, had a groove, *e q*, cut round its equatorial part, to represent the equator, and also other grooves, in parallels of latitude distant 4½° from each other. A deeper and wider groove, also, *p n*, was cut in it, extending from pole to pole in the line of a

Fig. 129.



single meridian. Things being thus arranged, the middle portion of a copper wire $\frac{1}{10}$ of an inch in diameter, and ninety feet long, was applied to the equatorial groove, in a point opposite the line of the meridian *p n*, which, being bent each way, in the equator *e q*, to meet at the groove *p n*, was continued toward each pole by a continual coiling and turning into the parallels of latitude. Finally, the remaining portions of the wire were covered with insulating varnished silk thread, and passed through the meridian groove toward the equator, and the two extremities, *a*, *b*, brought out for connection with the poles of a voltaic combination (40) (47). The whole was now covered with the pictured gores of a common globe, and in such way as to bring the poles of the electro-magnetic spiral as nearly as possible into the position of the observed terrestrial magnetic poles, viz., lat. 72° North, and lat. 73° South, and on the meridian corresponding with lon. 76° West of Greenwich.

The globe being now conveniently placed under a delicately-suspended needle A, Fig. 129, carefully neutralized in respect of the earth's action (164), electro-magnetic currents were caused to circulate through the spiral beneath the paper surface (40). When the globe was so placed as to bring London into the zenith, the suspended needle took the inclination of the dip, at that time 70°, and also the line of the variation, at that time about 24° West. On turning the globe round so as to bring other places of the same parallel under the needle A, the dip of 70° remained, but the line of declination changed its direction, becoming first zero and then increasing eastward, much in the same way as happens in the case of the horizontal needle. When the globe was turned so as to cause the pole to approach the zenith, the dip increased up to a point of verticity; and on turning it so as to bring the equator into the zenith, the suspended needle became horizontal. Continuing the motion so as to bring the south pole

toward the zenith, the suspended needle inclined in the opposite way, thus representing on a small scale all the phenomena of the horizontal and inclined needles. Professor Barlow thinks that he has proved the existence of a force competent to produce all the phenomena of terrestrial magnetism, without the aid of any body commonly called magnetic.

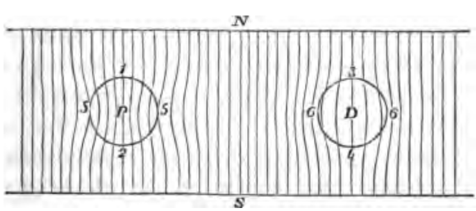
273. *Theory and recent Discoveries of Faraday.*—This distinguished philosopher, with his accustomed vigour of intellect and practised experimental hand, has not left the question of terrestrial magnetism unassisted by his immense labours. The general views which he is led to entertain upon points connected with the earth's magnetism may be thus stated:—Space devoid of matter, as also material space, that is, space in which matter is found, may be taken as being traversed by lines of force, operating, as it were, immediately through it. The condition of the space intercepted between the iron walls of the magnetic field, Fig. 59 (74), and Fig. 58 (72), may be taken as illustrative of this assumed physical condition of things. Now, although it may appear to many persons very difficult to conceive the existence of mere force independent of what we commonly call matter, yet we must recollect that, both in Electricity and Magnetism, it is with forces that we are principally concerned; and that, after all, it is far more difficult to conceive the existence of matter without properties of this kind than such properties without the matter; in fact, we recognize forces almost everywhere; but we recognize nowhere the ultimate atom of solidity of which matter is supposed to consist. All space, either vacant or occupied, presents for our consideration forces of various kinds, and the lines in which these forces are exerted. In viewing different substances in relation to lines of magnetic force, it is found that some bodies assume a position perpendicular to the direction of these lines; that is, they take an equatorial direction (74); others coincide in direction with the lines

of force, and take an axial direction (76). Pure space, devoid of matter, is conceived to have a magnetic relation of its own; that is to say, it permits lines of force to traverse it without in any way affecting them. The introduction of certain kinds of matter into space so occupied by force, will, on the contrary, change the existing state of the lines by either increasing or decreasing the facility of transmission. Common matter, when referred to lines of magnetic force traversing pure space, may be considered as being either zero, or as producing no change, or as being on one side or the other of zero; that is, as producing opposite effects. Hence has arisen a classification of two kinds of magnetic substances, viz.:—Those which point axially (76), and which have been termed Paramagnetic substances, and those which point equatorially, termed Diamagnetic. So that, taking the term "Magnetic" in its most general sense, as applicable to all the phenomena, we have the following division:—

$$\text{Magnetic} \begin{cases} \text{Paramagnetic.} \\ \text{Diamagnetic.} \end{cases}$$

When Paramagnetic or Diamagnetic substances are introduced into the magnetic field, they either increase or decrease the degree in which the force is transmitted, and thus disturb the uniformity of the lines. Paramagnetic substances, for example, concentrate the lines of force upon themselves, as represented by P in the annexed Fig. 130. Diamagnetic bodies, on the contrary, expand the lines of force, and cause

Fig. 130.



them to open outward from themselves, as represented by D in Fig. 130. Faraday calls this, for the moment, magnetic conduction. Paramagnetic bodies, when introduced into the magnetic field, always tend, from their power of concentration of force, from weaker to stronger places of magnetic action, and are urged in the axial line (76). Diamagnetic bodies, on the contrary, tend from stronger to weaker places, and are repulsed to the equatorial line (74). The force which thus urges bodies to the axial or equatorial lines is not a central force (179), but a force differing in character in the axial or radial directions. One may retain a very concise notion of this paramagnetic and diamagnetic relation, by conceiving that if a liquid paramagnetic body were introduced into the field of force, it would become prolonged axially, and form a prolate spheriod; whilst a liquid diamagnetic body would become prolonged equatorially, and form an oblate spheriod.

274. *Atmospheric Magnetism.*—By one of those happy trains of thought peculiar to great philosophical minds, Faraday conceived the idea of an atmospheric magnetism, and succeeded in proving that gaseous substances, when in the magnetic field, obeyed the same laws as all other matter. Thus oxygen gas, enclosed in a thin envelope, becomes drawn paramagnetically into the axial line, and is hence attracted by the magnet after the manner of iron (80), whilst olefiant gas, for example, is repelled diamagnetically into the equatorial line after the manner of bismuth. The nitrogen of the air does not appear to be either paramagnetic or diamagnetic, but to consitute the zero place in the scale of different substances. In thus demonstrating the paramagnetic property of oxygen, we arrive at the very important fact, that two-ninths of the atmosphere, by weight, consists of a substance, magnetic in character, after the manner of iron, a substance liable to vast changes in its physical conditions of temperature and density, and by which its magnetic character would be liable to vary, independently of all

consideration of magnetic force existing in the mass of our globe, considered as a magnetic body *per se*.

The earth itself may be considered as a spherical mass, consisting of both paramagnetic and diamagnetic substances very irregularly disposed; it is nevertheless to be considered on the whole as a magnet, and as an original source of power. The magnetic force of this great system is disposed with a certain degree of regularity, so far as our opportunities of examining it extend, which is only on its surface. The lines of force which pass in or across this surface are made known to us, as respects direction and intensity, by means of small standard magnets. The average course, however, of these lines and their temporary variations, either in the space above or in the earth beneath, are but very obscurely indicated through the same means. Our observations, in fact, do not tell us whether the cause of the variations is above or below.

The lines of magnetic force issue from the earth in the northern and southern parts, with different but corresponding degrees of inclination, and incline to and coalesce with each other over the equatorial parts (28).

The lines of force which proceed from the earth into space most probably return to it again; but in their circuitous course may extend to a distance of many of its diameters, to tens of thousands of miles. Space then forms the great abyss into which such lines of force as we recognize by our instruments proceed. Between the earth and this space, however, there is the atmosphere; it is at the bottom of this we live, and in the substance of which we carry on all our inquiries. Now this medium is, as we have just seen, highly paramagnetic, and may evidently become changed in its magnetic relations by any change incidental to temperature or pressure. None of these changes can happen without affecting the magnetic force emanating from the earth, and causing variations at its surface both in intensity and direction.

Having examined a variety of circumstances affecting the magnetic condition of the atmosphere, and the probable way in which such changes would affect the magnetic needle, Faraday concludes that the magnet, as at present applied, is not always a perfect measure of the earth's magnetic force. The intensity (254), for example, in oxygen, of a given density, would be different from those in expanded oxygen, although the same amount of lines of force and magnetic energy were present in both cases. To understand this, we have to consider that a needle vibrates by gathering upon itself the lines of force P, Fig. 130, and which otherwise would traverse the space about it. If the oxygen, therefore, be made dense, and a better conductor; then the magnet would carry on less of the force, and the oxygen more; it is therefore very important to know whether, when the magnet indicates an increased intensity; the intensity is due to the earth as a source of power, or to a change in the magnetic constitution of the surrounding space.* Considering that the magnetic state of the earth may not change whilst the oscillating needle, by the influence of the different conditions of day and night, or of summer and winter, may show a difference; so far the magnet, as at present applied, is not, according to this theory, a perfect measure of the terrestrial magnetic intensity. It is to the magnetic constitution and condition of the atmosphere, and the changes liable to be effected in it from changes in temperature, pressure, &c., that Faraday refers the annual and diurnal variation of the needle, and other periodical changes to which it is subject. Thus the position of the sun at a given place affects the atmosphere; the atmosphere affects the direction of the lines of force: the lines of force there affect those at any distance, and those affect the needles which they respectively govern. The sole action of the atmosphere is to bend the

* The author of this work first pointed out the necessity of placing the oscillating magnet in a space as nearly approaching a vacuum as possible. —Edinb. Phil. Trans. for 1836, vol. xiii. part 1.

lines of force, whilst the needle, being held by these lines, changes in position with the change of the lines. The needle is in fact a sort of balance, on which all the magnetic power around a given place hangs. Its mean position is the normal position. The fixation of the lines of force on the earth brings the needle back from its disturbed to this normal state; thus, as the earth rolls on in its annual course, that which at one time was the cooler becomes the warmer hemisphere, and in its turn sinks as far below the average magnetic intensity as it before stood above it. Now, since the sum of the forces passing out from the earth wherever there is dip, must correspond on each side of the magnetic equator, it is impossible that they should become more intense in one hemisphere or more feeble in the other, without corresponding effects upon the position of the magnetic equator itself, which may be thus expected to undulate, as it were, with the force, and move alternately north and south every year.

In the case of the diurnal variation, the whole portion of the atmosphere exposed to the sun, receives power to refract the lines of force, and the whole of that which covers the darker hemisphere assumes an equally altered but contrary state. It is as if the earth were enclosed within two enormous magnetic lenses, competent to affect the direction of the lines of force passing through them.

This hypothesis does not assume that the heated or cooled air has become actually magnetic, but is changed only in its power of transmitting the lines of magnetic force. It does not at present profess to apply to the magnetic or great secular changes of terrestrial magnetism, or to the cause of the magnetic state of the earth itself. With respect to variations of magnetic force not periodic but irregular (260), Faraday refers them to varying pressure, winds, currents, precipitations of rain or snow, &c., all of which may change the magnetic conduction of the air; and in this way the presence of a mere cloud near a station may do more than

the rising sun. Where the air is changed in temperature or volume, there it acts and there it alters the directions of the lines of force, and these by their tension carry on the effect to more distant lines, whose needles thus become affected also.

275. *Theoretical Review of Ordinary Magnetic Action.*—The first idea of ordinary magnetic phenomena was, as we have seen (13), the doctrine of Thales, who conceived the magnet to possess a species of animation; this doctrine, however, was superseded by the doctrine of magnetic effluvia (13), a principle which engaged the attention of philosophers down to the time of the celebrated Boyle. Lucretius, in his fine poem "De Rerum Naturâ," supposes that in the attraction of iron the effluvium of the lodestone displaced the surrounding air, in consequence of which atoms of iron flew toward the void, and in doing so dragged the iron toward the lodestone. Following this hypothesis arose the notion of an expansion and contraction of the effluvia, which being thrown outward from the magnet, seized upon ferruginous matter, and drew it by a collapse to the magnetic pole. Boyle resolves magnetic effluvia into indefinitely small atoms of magnetic iron, so indefinitely small as to permeate solid substances, and thus the lodestone is enabled to seize upon iron so forcibly as to raise it against its own gravity.* Gilbert imagines magnetic force to depend on what he calls "a formal efficiency," a "form of primary globes," of which forms there is one in the sun, one in the earth, another in the moon. Magnetism is the "formal efficiency" peculiar to the earth. The views of this truly great philosopher are, it must be allowed, very obscurely expressed, and, in common with all the preceding, were never practically applied in physico-mathematical science.

276. Des Cartes, casting aside all preceding doctrines, applied his famous system of vortices of ætherial fluid in explanation of magnetic action. The Cartesian hypothesis

* Essays on Effluviums, p. 33. London, 1673.

supposes matter to be indefinitely extensible without any other property, and to consist of atoms of different forms —every other quality being derived from ætherial elastic fluid continually revolving in vortices or eddies of various orders. The magnetic curves (28) he thinks an evidence of this. In no instance has the reasoning of this distinguished man been so persuasive as in the application of his theory to the phenomena of Magnetism.

277. Dr. Gowen Knight supposes magnetic action to depend on the circulation of a repellent fluid existing in space and in the pores of steel,* and capable of passing in and out of the magnet, or between magnetic poles, in one direction only. This hypothesis he thinks consistent with the observed phenomena. If, he says, a reason can be assigned for this circulation, then the "whole mystery of magnetism is solved." Attraction, upon this hypothesis, is the result of the fluid circulating from the pole of one magnet to the pole of another, Fig. 17 (28). Repulsion, on the contrary, is the result of opposed streams, Fig. 18 (28). Dr. Knight's work is by no means undeserving of notice, as being one of the first attempts to account for magnetic phenomena through the mechanics of matter and motion; and although strong exceptions have been taken to his postulates, the question how far they lead us to conclusions in accordance with observation still remains to be considered; of the agents employed by nature we really know nothing, except by the assimilation of effects with other agencies familiar to us. One of the great objections taken to this hypothesis is, that it is irreconcilable with the particular law of force deduced by Lambert and Coulombe, and should therefore be discarded.† This is, however, a somewhat hasty conclusion, since we have already seen, both experimentally (209) and by the researches of Faraday (274), that Magnetism is not necessarily a central force,

* Attempt to explain the Phenomena of Nature, &c. London, 1748.

† Library of Useful Knowledge. Magnetism, p. 33.

and that the law deduced by Coulombe and other philosophers is only a particular case of a more general form of magnetic action (215).

278. It is not unworthy of remark, that soon after the discovery of Electro-magnetism in 1819, Ampere developed his beautiful Electro-dynamic theory, and showed the mutual attractions and repulsions of electrical currents* according to a certain fundamental law; by assuming for a magnet a peculiar structure, he brings it under the dominion of this law, and by a most beautiful experiment shows that the circulation of electrical currents in a spiral wire, Fig. 43 (51), imparts to that wire all the properties of polarity in the direction of its length; and is finally led to conclude that a magnet has a current of electric fluid circulating about it in planes nearly perpendicular to its axis.

279. Following Dr. Knight's work, we have the fine work of Æpinus,† in which the author supposes the existence of an ætherial fluid, termed the magnetic fluid, the particles of which repulse each other, but attract, and are attracted by the particles of ferruginous matter. He further supposes that, in the absence of this magnetic fluid, the particles of ferruginous bodies also repulse each other, but attract the magnetic fluid; all these attractions and repulsions conform to the general law of central forces, being as the squares of the distances inversely. Æpinus had the great merit of reducing the laws of equilibrium of such a fluid and common matter to strict mathematical investigation, and of affording, in a great majority of cases, a satisfactory explanation of the phenomena. According to the hypothesis of Æpinus, the condition of a magnet is an induced disturbance of the magnetic fluid it contains, from which results a redundancy or accumulation of fluid in one pole, and a deficiency, or what may be termed redundant matter, in the other. This

* Rudimentary Electricity, second edition, p. 170.

† Tentamen Theoriæ Electricitatis et Magnetismi.

positive and this negative pole attract each other because of the mutual attraction between the redundant fluid of the positive pole and the redundant matter of the negative pole. Two positive poles repulse each other from the mutual repulsion of the particles of the magnetic fluid; two negative poles also repulse each other in consequence of the repulsion of the particles of redundant matter. Induction is the result of similar attractions and repulsions upon the magnetic fluid and ferruginous matter or distant iron by an overcharged or undercharged pole.

280. The French philosophers, startled at the assumption of a repulsive force in the particles of common matter, as being contrary to a fundamental law of gravity, changed the terms of the hypothesis of Æpinus, without altering virtually its application. Having assumed the existence of a primary magnetic fluid, they supposed it be a compound of two elementary principles, an austral and a boreal fluid, each repulsive of their own particles, but attractive of each other. Magnetic action is the result of a separation of these elementary fluids in each particle of the mass, and to which they are confined. This hypothesis originated with Coulombe about the year 1780, after the discovery of the opposite electricities, and the electrical theories of Du Fay and Symmer. It has since been more especially carried out in all its generality by M. Poisson, in his elaborate and mathematical analysis of the phenomena of Magnetism. M. Poisson proves that the sum of the actions of the magnetic elements in a given magnet are the same as if they proceeded from a thin stratum of each fluid occupying the surface only, and so distributed that their total action upon the interior of the body is equal to zero. We have only to substitute the term austral fluid for redundant matter or deficient fluid, and we have nearly the same result. Bonnycastle, in his application of this hypothesis, conceives the two fluids to have accumulated in opposite parts of a

magnet, which would make it identical with the hypothesis of Æpinus, by only changing the terms; whilst Barlow, as we have seen (264), confines the action to the surface of the magnet altogether, and refers the respective centres of force to two centres indefinitely near each other in the centre of attraction of the surface.

We have rather dwelt on these views of Æpinus and the French philosophers because of their admitting of the application of strict mathematical reasoning, and because of their being generally received as adequate to the explanation of magnetic action, no other equally substantive theories having been hitherto proposed; we must not, however, imagine that either of these hypotheses furnishes a real explanation of magnetic force, or that the existence of a magnetic fluid or fluids is, after all, anything more than a fiction of the mind, employed as a temporary substitute for truth. Still they greatly assist us in arriving at what we may consider as a true theory, viz., a resolving of classified facts into other facts still more general, and the final development of one great ultimate fact common to them all. Few who have considered the more recent progress of Electricity and Magnetism, more especially the brilliant researches of Faraday, will be disposed to place much confidence in the notion of electrical and magnetic fluids, and who will not perceive that the phenomena depend in all probability upon a principle of causation of a very different character. Grove, reasoning on the correlation of physical forces, considers Magnetism as a mode of motion caused by certain undulations or vibrations in the particles of common matter. Faraday, as we have seen,* disencumbers himself of the common theory of material atoms, and refers the phenomena to certain lines of force traversing space (273), and the relations which various substances have to these

* Rudimentary Electricity.

lines. In all these speculations the student will do well to remember that it is quite in vain to seek for an adequate explanation of causation in the abstract; all we can hope to arrive at is, as just observed, the resolving of phenomena into an intelligible sequence, and showing their dependence on some great ultimate principle reducible to a fact. This it is which constitutes a perfect theory.

IX.

THE MARINER'S COMPASS.

Early History—The Mariner's Needle—Dr. G. Knight's Inquiries—Best Form and Conditions of Compass Bars—Modes of Suspension—Scoresby's Compound Bars—Employment of more than one Needle in the same Compass; various kinds of Sea-Compass—Committee of Inquiry into the State of the Compass Department of the Navy—The Admiralty Compass—Application of Magneto-Electrical Action to the Movements of the Needle and Compass by the Author—Magnetic Observatory at Woolwich—Mode of testing the Compasses of the Royal Navy—Local Attraction of Ships—Iron Ships—Deviations of the Compass on Shipboard—Methods of Correction.

281. We have already described (148) in a general way the nature and use of the mariner's compass, and have further explained (243) the terrestrial magnetic variations to which it is subject; there remain, however, to be yet considered some other circumstances connected with this superb invention demanding especial attention; these relate principally to certain improvements in the construction and use of the compass, and the deviations to which it is liable in consequence of the local attraction of a ship, especially of an iron ship, together with the methods hitherto practised for determining and correcting such deviations. Upon a review of the immense importance of this subject, therefore, as a branch of Magnetism, we have thought it desirable to devote a few pages to the exclusive consideration of this wonderful instrument, which, taking it in all its generality, may be considered as the polar star of magnetic science.

282. The application of the directive property of the lodestone (6) to the purposes of perilous journeys on land, and to the art of navigation, may be considered, probably,

the first, as it was certainly the greatest practical use to which Magnetism has been as yet made subservient, and furnishes an invaluable lesson in attempts to investigate nature by a careful collection of facts, however trifling the facts may appear. The person who first observed the attraction of one particle of iron toward another, little thought of its leading to a means of guiding the mariner over a perilous and pathless ocean in the midst of darkness and tempest, without any other light to cheer his way than that of a small lamp shining on a piece of steel; yet such has been the result of the discovery of magnetic agency. By whom the mariner's compass was first invented, or with what nation it may have originated, has never been circumstantially determined; it is, however, pretty certain, as observed by the indefatigable Humboldt, that, at least seven hundred years before it was employed by European nations, Chinese craft were sailing on the Indian Ocean under the supposed guidance of south magnetic indication: this, together with the proved use of the common compass in China from the earliest times of which we have any record, the terms the Chinese employ to designate it, and the prevailing idea in that country that the needle points south, go far in corroborating the opinion that the mariner's compass originated in China, or in some part of India (8). A rude form of compass is said to have been invented in upper Asia, and from thence conveyed by the Tartars to China.*

The employment of the needle in navigation appears to have been first generally introduced into Europe towards the end of the thirteenth, or the beginning of the fourteenth century, and is attributed to a Neapolitan, a noble citizen of a town of Principato, which has ever since borne the figure of a mariner's compass as the arms of the territory.

283. The magnet, when first used in navigation, consisted of a common sewing-needle, which, being rendered magnetic,

* Mrs. Somerville, Physical Sciences, p. 338.

was passed through a piece of reed or cork, sometimes forming a cross, and allowed to float on the surface of water; hence, probably, the term "magnetic needle." Such, at least, was the practice of the captains navigating the Syrian seas in 1242.* Subsequently, however, the needle was increased to about six inches in length, and suspended on a point, in a white china dish filled with water, probably to prevent it from falling toward the side of the vessel. The present form of the mariner's compass (148) is undoubtedly of comparatively recent date, and it is equally certain that advances toward refinement in its construction have been very slow; indeed, so lately as the year 1820, Professor Barlow, who was directed by the Board of Admiralty to investigate and report on the state of the compasses furnished to the royal navy, states, "that at least one-half of them were mere lumber, and ought to be destroyed." Flinders also observes, "the compasses of the royal navy are the worst-constructed instruments of any carried to sea."

284. We are indebted to Dr. Gowan Knight † for many valuable attempts to improve the mariner's compass in this country. Almost all the needles in merchant ships were, at the time he wrote, in 1750, composed of two pieces of steel, bent in the middle, and united in the form of a lozenge or rhombus, as in the annexed Fig. 131. This form he considers as very objectionable. Having examined twenty of these needles, he found them all to vary from the true direction. Should the temper of the steel be unequal, the hardest sides will have, he says, the greatest directive power. Besides this, the sides which nearest agree in direction with the earth's magnetism, when the needle deviates from the meridian, will tend to preserve the decli-

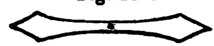
Fig. 131.

* Klaproth, Lettre à M. Humboldt, p. 57.

† Phil. Trans. 1750, vol. 46.

riation more or less; hence many of the needles and cards he examined appeared to have a very small directive force. The needles employed in the navy were made of a single piece of spring-tempered steel (87), broad toward the ends, which were pointed, and tapering toward the middle, as represented in the annexed Fig. 132.

Fig. 132.



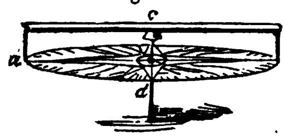
This form, although less objectionable as to direction, was still imperfect. Such needles, he says, acquire six poles (26); these may be made apparent by the experiment with steel filings (28). The needle has not, from this circumstance, the same amount of directive force; the greatest directive force obtains when the magnetic curves extend from two polar extremities. Dr. Knight concludes, after a careful inquiry, that a regular parallelopiped, or straight bar narrow-edge needle, as represented in the annexed Fig. 133, is the most advantageous form for a compass-needle.

Fig. 133.

c

He thinks that if the hole at *c* for the suspension-cap could be avoided, it would be very desirable, and for the reasons just assigned. With this view he was led to suspend the bar upon an agate attached to its under surface, the card being secured beneath the bar through the intervention of a ring of brass, of sufficient weight to bring the centre of gravity of the whole system below the point of suspension. Such was the form of needle and card afterward in use for some time in the royal navy; and it is still worthy of serious attention, how far this kind of suspension may not be improved in its application to the light talc discs now employed, so as to avoid the weight of the brass ring. As, for example, in the way indicated in the annexed Fig. 134, in which *a c b d* represents a light disc of talc, attached by two fine wires at

Fig. 134.

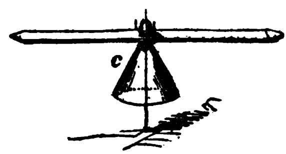


the extremities of the bar; *c*, the point of suspension which is beneath the bar; *d* the standard of support.

It is not unworthy of remark, that the Chinese method of suspending the compass-needle, already described (122), is based on the same principle; the point of suspension in the Chinese compass is invariably below the centre of gravity of the needle, the needle being perfectly continuous. The sensibility and delicacy of these instruments are quite surprising.

The Dutch employed for several years a conical brass bell in the suspension of their compasses, which they attached below the centre of the needle, as indicated in the annexed Fig. 135. All these contrivances, however, became eventually superseded by a simple suspension-cap, fixed in the centre of the needle, as at *c*, Fig. 133; but of all the methods of suspending the magnetic needle, that by means of a silk fibre (118), is undoubtedly the most delicate although not perhaps sufficiently practical for sea-going purposes.

Fig. 135.



285. Dr. Knight further inquires as to the best material for the cap of suspension. The caps at that time in use were either made of brass, or a hard, mixed metal, similar to the metal of a reflecting telescope, or otherwise containing a centre of crystal or agate. The first, he says, will only admit of a brass point; the others being costly, he was led to try glass; but upon the whole he concludes that a cap centred with agate has the least amount of friction. For a point he chose a common sewing-needle. Of late years the centres of the caps of compass-needles have been occasionally formed of ruby, and a point employed for their suspension formed of native alloy, which is found to be harder than steel.* This question is one of much consequence to the working of

* A valuable practical paper, by Capt. Johnson, R.N., on this subject, will be found in the Reports of the British Association for 1840.

a ship's compass; the great weight of the needles and cards at present employed, is very liable to work a hole in the agate centres, especially when at all defective in structure; and so eventually destroy its action; hence it is still very doubtful whether a fine and well-hardened point of brass, worked to fit a central cap of hard mixed metal, is not after all as well adapted for the purpose of a delicate and lasting suspension as any which can be devised. Mr. Stebbings, a celebrated optician at Southampton, employs ruby for the points as well as the caps, worked to fine globular surfaces of contact.

286. The question of the most favourable conditions in the construction of a compass-needle was, in the year 1821, further investigated by Capt. Kater, F.R.S., who came to the conclusion that the best form was the pierced rhombus (Fig. 131); that hardening the needle throughout was injurious to its capacity for magnetism, and that the directive force depended on the mass, and not on the surface. These deductions have not certainly been so satisfactorily confirmed as to entitle them to unlimited confidence; indeed, it is now universally admitted, that a bar of small breadth, Fig. 132, suspended edgewise, and hardened throughout, as practised by Gowan Knight, is after all the best form for the needle of the mariner's compass: this kind of needle, therefore, is usually employed.

Captain Kater's conclusion, that the directive force of a magnet is dependent on its mass, has yet to be reconciled with the fine experiments of Professor Barlow (239), and the more recent inquiries already adverted to (228).

287. It may be worth while to notice a few conclusions arrived at by Michell and some of the old writers on this subject. Michell observes that all single unarmed bars should have a certain length, in proportion to their weight. A bar 6 inches in length, and ½ an inch wide, should weigh 1¼ ounces. The steel must be free from veins of iron, and

* Phil. Trans. for 1851.

hardened with a full heat, but not with too great a heat; for that is as bad as the other extreme. That is the best steel which will receive the greatest hardness with the least degree of heat.

Michell recommends very light bars for the purpose of a compass-needle, because the friction, he says, increases in a much greater degree than the magnetic power; he recommends the caps for such needles to be of gold alloy, the alloy in large proportion. He found a long needle with this cap to vibrate on an irregular blunt brass point for fifteen minutes, whereas, with a common brass cap, and a sharp steel point, it would scarcely vibrate at all.

Mr. Timothy Barlow, in a good practical work,* in which he treats of the "fashion of the compass-needle," says that the steel must be first hardened to brittle hardness; it should be anointed with soap before being put into the fire, by which the black will easily scale off. The needle is to be now placed on a bar of red-hot iron; when "you shall see it turn from white to a yellowish colour, and then to blue;" now throw it on a table and let it cool; and "so he is of a most excellent temper." For the form of the needle he approves of an open ellipse, but is a great advocate for light cards and needles.

288. Having already considered the questions relating to the kind of steel, temper, and methods of magnetizing (89) (99), it will not be requisite to enter further upon these questions here. We have merely to observe, that in the construction of bar-needles for the mariner's compass, it has been thought of advantage to employ two or more magnetized steel plates, and unite them into a sort of compound magnet (19, 113). The Rev. Dr. Scoresby, at the Bristol meeting of the British Association, in 1836, first proposed this method for compass-needles, and insisted on the necessity of tempering the plates throughout their length. Compound bars of thin steel plates, on Scoresby's construction,

* Magnetical Advertisements; London, 1616.

have since been employed for the compasses of the royal navy.

289. It was customary, above half a century since, to apply more than one needle to the same compass-card; this practice has of late years been again revived, with additions and improvements, more especially in the compasses of H.M.'s ships; in which from three to five needles have been employed. Cavallo, whose works on electricity, magnetism, and other branches of physics, are highly prized in the world of science, has in reference to this practice the following remarks:—"Compasses for the sea service formerly, and some even at present, are made in the following improper manner:—The brass cap is fastened to the middle of a circular card, upon which the various points of the horizon, as the east, west, &c., are marked. On the under part, two pieces of magnetic steel are stuck fast to it, so as to be parallel, and to stand about half an inch distant from one another, the pin upon which the whole is suspended passing between them."* The object in using more than one needle is evidently a greater directive force; this advantage, however, as observed by Professor Barlow, cannot be obtained without an increase of weight of steel, and as a necessary consequence, a greater amount of friction on the point of suspension. Unless, therefore, the directive force increase in a greater ratio than the loss by friction and wear of the centre, little advantage is obtained. The only favourable circumstance is in the case of heavy cards, made purposely heavy, in order to steady the motion likely to be induced in it by the rolling and pitching of the ship. If the card be encumbered by a dead weight, the power of a single needle is frequently insufficient to bring it accurately into its meridian, and thus the essential quality of the compass is sacrificed; now, by employing several bars, we not only add to the weight of the card, but we also add directive force,

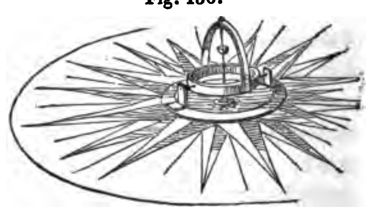
* Treatise on Magnetism, by Tiberius Cavallo, F.R.S.; London, 1800.

and thus in great measure avoid this defect. It will be found, however, as we shall presently show, that the use of more than one bar-needle and heavy cards are quite unnecessary; any method of steadying a compass by mechanical impediment to motion, whether by friction on the point of suspension, or on any other point, is evidently a hazardous practice. The mariner, deceived by the apparent steadiness of the compass-card, may find himself in peril before he is aware of his danger, the impediment to motion being such as to place the compass in error as to direction.

290. As a great and almost endless variety of forms and contrivances for the mariner's compass, with a view to its further improvement, have been proposed, it may not perhaps be undesirable to advert to some of these inventions.

Compass by Preston and Alexander.—The great contrivance universally resorted to for the purpose of meeting the difficulties arising from the pitching and rolling motions of the ship, is, as we have already explained (148), the method of gimbalds, by which, under any inclination, the compass-bowl remains vertical. In Preston's compass, an inner and small set of gimbalds are applied also to the needle and card, the whole resting by a descending point upon an agate centre, as shown in Fig. 136. This agate centre is further preserved vertical and steady by means of a pendulum action, and a ball and socket joint, not drawn in the figure. The interior gimbalds, &c. have been found very beneficial in preserving the needle and card steady.

Fig. 136.



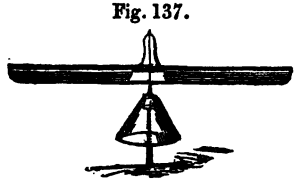
Mr. Grant Preston also contrived another kind of compass, in which the needle and card were fixed on a vertical axis moveable between two centres, and in 1832 obtained a

patent for steadying the needle by passing a delicate-pointed axis of support through a fine hole in a semicircular arc, or plate of brass, attached beneath the needle.

Pope's Compass.—In this compass, two or more bar magnets are now employed. They are set parallel, and allowed to take any degree of inclination of which they are susceptible; each bar being hung on a transverse horizontal axis, applied to pivots fixed to slits in the compass-card. The freedom of motion of the needles in a vertical plane may certainly be useful in high latitudes; but beyond this, no advantage is derived from it. This compass originally had only one needle hung in the centre of the card.

Compass by Captain Walker, R.N.—In this compass, a double set of suspensions are employed, one over the other. First, the card is suspended on a fixed vertical axis, passing through a small hole in a plate of brass, attached to the under side of the needle, upon Mr. Grant Preston's principle, and terminating in the agate cap, which is somewhat elevated. This axis of support is fixed upon a conical bell of brass, such as formerly employed in the Dutch compasses, and shown Fig. 135. This bell is again suspended on a point and agate centre beneath, as represented Fig. 137. The object contemplated, is a steadying of the needle by a refinement on Preston's patent, and a decrease of friction, by allowing motion to the point of suspension of the needle through the intervention of the brass bell. The bell, however, may be fixed, if found desirable, by means of a wooden cone, which is to be placed within it, over the point of suspension.

Fig. 137.



The needle may be considered as a sort of combination of the flat and bar-edged needles, the latter being nearly divided in the centre, but extending edgewise under the flat bar up to its extremities, as indicated in the figure.

Compass-Needle by Captain West, R.N.—The oscillations and movement of the needle are checked by the occasional friction of an ivory ring, through which the vertical axis of suspension freely passes. The ring is fixed centrally beneath the needle by means of a semicircular arc of light brass wire, attached to each of its extremities, as in Preston's patent. This contrivance has been found effectual.

Compass by Captain Boutakoff, of the Imperial Russian Navy.—The needle is fixed nearly in the line of the dip, which can be changed to suit the latitude; the card is figured on each surface, and so fitted that, in crossing the magnetic equator, it can be turned over with the needle. Captain Boutakoff thinks that by this method he avoids at least one-half the vibration.

Dent's Compass.—In this compass four thin, wide magnets of steel plate are applied edgewise to the under surface of the card, parallel to each other, and the whole is fixed on a vertical steel axis, as practised by Preston, but is beautifully set up between two jewels as centres, after the manner of the balance of a chronometer; so that very little friction arises in the pivots of the axis. The centre of gravity and centre of motion are made to coincide. To check any inconvenient oscillation, there is a light steel spring: this spring, by a simple lever action, may be pressed gently against the axis of the compass.

Stebbing's Compass.—The needle and card are suspended on a ruby point and agate centre, which are carefully worked to extremely fine spherical and corresponding surfaces of contact; so as to avoid all abrasive action, the compass-fly is of silk, secured in a light circular frame of brass attached to the needle; the whole is enclosed in a glass bowl, and is perfectly transparent. This compass is usually fitted in the deck, so as to be illuminated at night by the lights in the cabin beneath.

Submerged Compass.—About the year 1779, Dr. Ingenhouz made some experiments on a magnetic needle immersed

in water. He found that the water by its resistance as a medium, tended to steady the needle, without diminishing in any sensible degree the directive force. This led him to think of enclosing the needle for sea purposes in some fluid; a proposition which, although deserving much consideration, was not at the time adopted. It has, however, since been partially resorted to, and some instruments of this kind by Crowe and Preston have answered extremely well. The compass-bowl or kettle (148) being fitted water-tight, is filled with oil or spirit, or some fluid compatible with the durability of the compass. This instrument is occasionally employed in the royal navy, and is found especially useful in boats when subjected to a short jerking motion.

291. *Admiralty Compass.*—The admitted defects in the compasses formerly supplied by contract, by the lowest tender, for the use of the royal navy, induced the Board of Admiralty, in the year 1820, to appoint Professor Barlow to examine the compasses then in store. Mr. Barlow found these instruments so defective, that, as already observed, he states, in his report, "at least one-half were mere lumber." Very little amelioration, however, in this state of things appears to have taken place until 1838 to 1840, when the board appointed a committee for further inquiry. One of the results of the investigations by this committee has been the production of a compass called *par excellence* "the Admiralty Compass." In this compass four of Scoresby's compound magnetic bars are employed, secured together with the card within a light ring of brass; the card is of mica, covered with thin paper, the impression of the cardinal points, &c., being struck off subsequently to its being cemented to the surface of the talc, so as to avoid all distortion of the surface by shrinking; the caps are of agate or ruby, worked to the shape of the points of suspension, which are of native alloy (285). Spare points of steel are also supplied; these are gilded by the electrotype process. The compass-bowl is made of copper, with a view to tranquillize the oscillations of the needle,

after a form of compass previously submitted to the committee by the author of this work. The principle, however, as thus employed, is very inefficient, the great condition being the application of a dense ring of copper immediately round the poles of the needle. Each compass is furnished with two spare cards, a light and a heavy card, and six spare pivots. When the light card is not sufficiently steady, then the heavy card is directed to be employed, together with the particular pivot-point especially appropriated to its use; the card is levelled by balance slide-pieces, as in the compass previously submitted by the author for the consideration of the committee.

This compass, although not possessing any superior excellence as a steering compass, having, with a sensible suspension, proved very unsteady at sea,* is nevertheless carefully and beautifully constructed, especially in its adaptation to the purposes of an azimuth compass, into which form of compass (150) it is convertible. In this case the instrument is placed on a stand, the glass cover removed, and the azimuth circle fixed on its upper margin. The arrangement is such that the sight-vane and prism (150) can be turned without interfering with the other parts of the instrument, as will be hereafter explained (298). The bottom of the compass-case also can be removed so as to light the card from beneath.

292. Upon a review of nearly all the several forms of mariner's compass to which we have just adverted, it is evident that the simplicity of construction requisite to every sea-going instrument has been materially compromised, all the contrivances are more or less complicated, and, as a necessary consequence, more or less costly. That would

* See a valuable work by Capt. Johnson, F.R.S., Capt. R.N., "On the Deviations of the Compass," p. 51, published under the sanction of the Lords Commissioners of the Admiralty, as also reports from H.M.'s ship *Asia*, and some other vessels.

be the great perfection of the mariner's compass which should combine steadiness, under the variable motions of the ship, with great sensibility and simplicity of construction, so that in case of any mishap or error arising from the wear and tear of the respective parts, there may be nothing to correct, which any ordinary mechanic, or, if in the navy, which the ship's armourer could not easily manage. Unless, therefore, it can be shown that such complex arrangements are absolutely requisite, they are best avoided. No sufficient reason, for example, can be assigned for the employment of from three to five compound magnetic bars of costly and difficult construction; supposing it were proved, from the evidence of experience, as well as theoretically, that a single and simple bar-edged needle is even more than adequate to any required practical purpose. Beside this, there are some not unreasonable objections to the use of several bar-needles; the similar poles, for example, tend to destroy each other's power (111); and if the magnets be not very accurately parallel, and carefully magnetized and placed, the card may be in error as to direction; to avoid this, it is requisite to suit the card to the direction after the needles are applied.

We may further observe, that it would be unphilosophical to employ two cards of unequal weight, with especial pivots adapted to each card; and with a view to particular adjustments under motion, and to the obtaining a steady compass by the aid of friction, provided all the advantages to be derived from such adjustments could be arrived at with one card, and by more simple and efficient means; it would also be quite superfluous to mount a compass on two consecutive pivots, as in Fig. 137, when one point of suspension is sufficient. Such arrangements, therefore, however ingenious, are not desirable, unless absolutely requisite to the perfection of the instrument. It is to be remembered that, in the construction of the mariner's compass, the abstract

perfection we seek to obtain, is the image of a small horizontal circle duly graduated, and divided into thirty-two rhumbs or points, which, floating as it were in a fixed position in space before the eye of the steersman, directs the guidance of his ship. It is, in fact, the ship which we must suppose to move into various positions, not the compass; that should be so delicately and sensibly hung as to come as near the condition of this ideal aërial compass as may be.

293. *Mariner's Compass by the Author.*—Impressed with these views, the author of this work was, in the year 1831, led to the construction of a particular form of mariner's compass, combining simplicity of construction with great sensibility and stability. The following is a brief notice of this instrument, as constructed by Messrs. Lilley, opticians, Limehouse:—

The needle consists of a light bar-edged magnet, from 5 to 7 inches in length, furnished with a central cap, as in Fig. 133. The bar is carefully worked, hardened and tempered throughout; and, previously to being magnetized, is accurately poised in a horizontal position (156).* Being thus poised, two small sliders of silver, weighing each about twenty grains, are fitted to the bar, so as to move upon it with friction. They are placed over a mark midway between its centre and extremities, the whole being perfectly poised; the bar is now rendered magnetic, and in such a manner as to admit of the centre of the various magnetic curves (28), Fig. 16, falling immediately on the point of suspension. The small magnetic dip incidental to the bar, is corrected by moving one of the silver sliders a little toward the centre, and the opposite slider a little toward the extremity. By this method, we have always what may be considered as the same quantity of magnetism, matter, and motion, on each side the centre, since the difference in the angular inertia of the silver

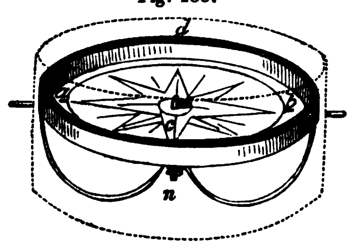
* This instrument has become the property of Messrs. Lilley & Son, opticians, West-India Docks, and is made with great care and perfection in the workmanship.

sliders is sufficiently small to be neglected; the bar, therefore, is so far deprived of any tendency to persevere in a state of movement, from the motion of the ship. The magnetic force of this bar-needle, from the particular way in which it is made, is so considerable, as to lift at either pole three times its own weight of iron, and will produce, according to Scoresby's method of deflections (134), a deviation of 22° at a distance of twice its length from the centre of the trial-needle. These bar-needles are nevertheless very light.

The needle as thus constructed is attached to a very light disc of talc, in a single piece, and on which the requisite points and graduations are conspicuously and clearly painted; by which means the presence of a paper surface is avoided. The whole is balanced in an east and west direction, that is, transversely to the direction of the needle, by a light cross bar of brass, furnished with small sliders, in the way just described.

Things being thus arranged, the needle is suspended upon a central point *c*, Fig. 138, proceeding from a double curved bar *a n b*, fixed as a diameter to a dense ring of copper *acbd*, and in such way as to admit of the poles of the magnetic needle *a b* moving just within the ring, and so near the copper, that the magneto-electrical action already explained (58, 60, 63), can sensibly restrain any oscillation to which the needle may become exposed. We thus bring to bear upon the needle an invisible agency, which, without offering any rude, common, mechanical impediment to motion, such as friction, or in the least degree interfering with the sensibility or direction of the instrument, restrains as if by a magic hand its disturbed movement, and confines it like the

Fig. 138.



ideal card to which we have adverted, in a given position in space.

294. The author has investigated* the magnetic conditions of this phenomenon, and has shown that the restraining force with a magnet of a given power, is as the quantity of the copper within the sphere of action directly, and as the squares of the distances from the magnetic polar extremity of the needle inversely (174, 175), the matter of the copper being supposed to be condensed into an indefinitely thin stratum, and taken at a mean distance from the pole of the bar at which the sum of the forces may be supposed to produce the same effect as if exerted from every part of the mass. The energy of a ring of copper in restraining the magnetic oscillation is therefore as its density. It was also further found that with a given magnetic tension the restraining power of the copper no longer sensibly increased with the thickness of the ring, and that hence the required thickness was different for different needles. It is requisite, therefore, to have the poles of the bar as near as possible to the surface of the ring; to give the copper the greatest possible density, accumulate it immediately about the poles of the needle, and give the ring a greater or less degree of thickness sufficient to exhaust as it were the magneto-electrical energy of the magnet to be employed.

The ring and axis of suspension are accurately turned and centred in a lathe; the axis of support *c*, Fig. 138, is pointed at each extremity, and admits of being reversed in position by turning it over, and fixing it in the reverted direction; we have hence a spare point always at command. The cap, also, can be renewed when requisite. The points and centres are usually made of very hard mixed metal, which has been found less liable to abrasion than agate and steel points.

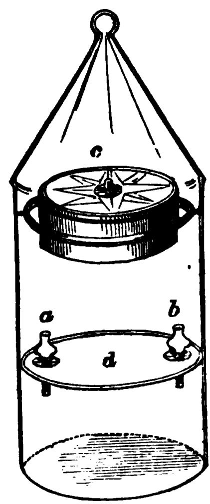
Things being thus prepared, the whole is placed within a cylindrical copper case, faced above and below with plate-

* Phil. Trans. for 1831, p. 497.

glass covers. As indicated in the last figure, the whole is hung in gimbalds, in the usual way (148).

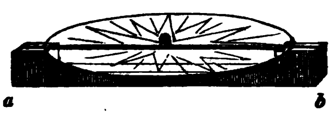
295. The card being beautifully transparent, a small quantity of light placed beneath, and a little on one side of the compass, is sufficient to illuminate it at night. With this view, it is intended either to fit the compass in the deck, and light it from the cabins beneath, or otherwise, in a binnacle of a very simple construction, shown in the annexed Fig. 139, especially adapted to its use. This binnacle is of wood, and of an octagonal or cylindrical form, about two feet six inches high, the compass being hung on its upper part, at *c*. About twenty inches beneath the compass, there is a platform *d*, carrying two small spring candle-lamps *a b*, hung on pivots in holes in the platform, one on each side; one of these is sufficient for the purpose of illumination. The candles are easily replaced without disturbing the apparatus, they being previously secured in spare spring sockets, made to drop freely into the body of the lamp, which need not be taken out. There are some small holes round the compass at *c*, for ventilation, and a small door below, through which the requisite manipulations are easily carried on. This method of illumination is extremely economical, clean, and efficient, and requires no trimming or attention. It is far superior to the common method with oil-lamps,* which occasionally proves very troublesome, dirty, and inconvenient.

Fig. 139.



* The compass may be illuminated in this way at the rate of one penny for seven hours, the effect being a subdued and beautifully soft transparent

Fig. 140.



296. When the card and needle are not in actual use, they are to be secured in a soft iron keeper (10), as indicated in the annexed Fig. 140, which represents the needle as resting in slits, cut for its reception in two masses of soft iron, formed at the extremities of a soft iron bar *a b;* this keeper is fixed in a shallow square box, with a slide cover. It is most important to the mariner to attend to the preservation of his compass in some such way as this. The instrument as usually stowed in the store-rooms on shipboard is very liable to be ruined in various ways, and its polarity either greatly weakened, or altogether destroyed (110). If the north pole of the needle be merely placed in opposition to its natural direction, and toward the south pole of the earth, that alone is sufficient to disturb and weaken its magnetic development (14, 101).

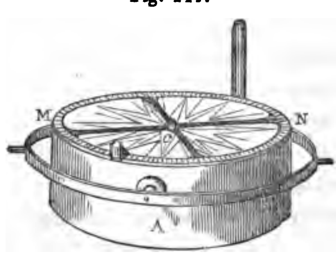
297. It not being the author's object to dwell longer on this particular form of sea-compass than is requisite to the interests of navigation and scientific inquiry, any lengthened report of its operation, as observed in numerous instances, must necessarily be avoided: we may, however, observe, that it has been extensively and very successfully employed in the merchant navy; it has been also employed in the fleets of the Honourable the East-India Company, in numerous ships of foreign powers, and in several of Her Majesty's ships; and it appears, upon the whole evidence of experience in every class and kind of vessel, that there is no condition requisite to the full practical perfection of the mariner's compass which it does not satisfy; and considering the extreme perfection and beauty of the workmanship by

light. The lamps and candles are supplied by Mr. S. Clarke, 55, Albany Street, Regent's Park, London. The candles are warranted to stand in any climate. Three years' consumption may be packed in a box occupying about two square feet.

the makers, its cost is comparatively small, it being about half that of the Admiralty compass as commonly supplied to the ships of the navy. In the heavy seas about Cape Horn and the Cape of Good Hope, the card was not found to oscillate more than from ¼ to ½ a point each way. The only complaints which have arisen, in a few instances, have been referable to abrasion of the agate centre in some of the instruments first made, arising from wear and tear of the point of suspension. The agates, in these cases, were examined, and found defective; all such defects have been since removed. It may not be unworthy of remark that this compass has proved especially steady in steam-ships fitted with the screw propeller.

298. The application of magneto-electric action as a means of steadying the compass in its meridian is of singular importance to the azimuth compass (150), where angular distances require to be accurately measured. An improved azimuth compass, by Messrs. Lilley, has been lately produced, in which the needle, nailed as it were to its meridian by the influence of a dense ring of copper, may be considered as being without any oscillation. In this instrument the margin of the card is graduated to twenty minutes, the plate-glass cover contains a metal centre, about this centre the pivot of the upper part of the verge, carrying the sight-vane and prism (150), revolves, leaving the compass-bowl and its contents fixed, as in the azimuth compass of the Admiralty committee; all this part of the instrument, therefore, remains unaffected: this is of the utmost importance, especially in iron ships. The lubber-line in this instrument, as constructed by Messrs. Lilley, is set on a delicate index, which acts

Fig. 141.



as a stop when the reading is being taken, and is always directed to the ship's head. In the annexed Fig. 141, M N represents the revolving part of the verge, which can be turned about the centre *c* fixed in the glass plate beneath; A, the body of the instrument, remaining fixed.

299. It may not be unimportant, before dismissing the consideration of magneto-electricity as a restraining force in the disturbed movement of the compass on ship-board, briefly to notice a conclusion arrived at by the compass committee of the Admiralty relative to the operation of this force, the question being one of singular importance to the future interests of navigation. The author had, six years previously to the appointment of the committee in 1837, completely worked out all the great practical deductions bearing on the application of magneto-electrical action in steadying the movements of the mariner's compass, and had shown how the magnetism of the needle itself might be made the means of restraining its own oscillations. The questions of thickness of metal, density, and magnetic force had all been completely investigated by taking the magnetic vibrations within thin concentric circular laminæ of copper turned up in the form of rings.* It was easy to determine with a given magnet, and by means of the formula previously deduced (66), the precise effect of any one of the concentric rings, both as to position and distance, or of any number of rings combined, or by varying the magnetic force, the effect due to different degrees of magnetic power; in this way, as already observed (294), it was proved that the magneto-electric energy, or restraining force, was as the magnetic intensity directly, and as the second powers of the distances inversely. The experimentalists of the compass committee, however, not having probably considered these facts, were led, upon an examination of the compass submitted by the author, to try the influence of a solid copper bowl, of a given thickness, on the magnetic oscillations, and then to

* See Phil. Trans. for 1831, p. 497.

cut away or turn down the bowl $\frac{1}{10}$ of an inch at a time, so as repeatedly to reduce its substance; examining as repeatedly the magnetic oscillation at each reduction. The conclusion arrived at by the committee was, that a thin bowl of copper was as efficacious in restraining the magnetic vibration as a thick bowl; and that hence if the magnetic needle and card were enclosed in a copper compass-kettle, the use of a copper ring condensed about the poles of the needle, as employed by the author, would be superseded. Upon this very hasty conclusion the committee proceeded to act in the construction of the Admiralty compass. With respect to the experiment itself, it was anything but refined: perhaps it may be considered as somewhat clumsy when compared with the method of concentric laminæ. For the force decreasing as the second powers of the distances inversely, it was, after all, not likely that any great effect would result from the distant parts of the bowl; the induced restraining force would be almost entirely, if not altogether, confined to that part of the copper bowl immediately opposed to the poles of the needle: the experiment, therefore, was most unnecessarily elaborate and costly. It is certainly possible that a magnet of a limited power, with its poles placed at a certain distance from the copper, might have all its magneto-electrical induction exhausted as it were, by a certain thickness of copper, as the author had already shown. This, however, was only a limited or particular case of a great physical action, but which the committee failed to investigate in all its generality. Had the experimentalists tried other magnets, and allowed their poles to oscillate near the surface of the copper, they would not have come to the same conclusion.

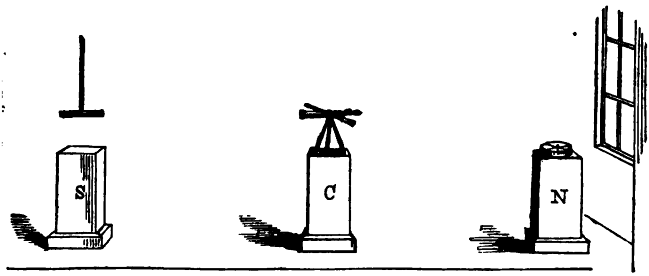
The experimentalists, however, had great confidence in their deduction; but they evidently failed in producing any amount of tranquillizing power; since, by the extract from the work published under the sanction of the Board of Admiralty, already referred to (285), as also from various

official reports, the compass proved "too unsteady for use under the heavy rolling motions of a ship of the line," also in "some steam-vessels;" it hence became requisite to call in the aid of friction by the employment of a heavy card, in order to curb the irregular movements.* The experiment, therefore, by the compass committee was incomplete, and the deduction from it practically false: to obtain anything like a competent tranquillizing power, it is absolutely requisite to employ a powerful bar, and place the copper in a thick dense ring, immediately about the poles of the needle. It is in fact notorious to all those acquainted with the Admiralty compass, that little or no effect is produced by the influence of the thin copper bowl on the oscillations of the card. This subject is undoubtedly important, and is still open to much further and beneficial investigation. The most energetic metal has yet probably to be discovered.

300. *The Compass and Magnetic Observatory.*—Much benefit did undoubtedly arise to the public service by the appointment and labours of the committee of inquiry into the state of the compass department of the navy, more especially in the establishment of a regular and well-ordered observatory at Woolwich, for examining and perfecting the compasses intended to be employed in H.M.'s ships; and it is to be regretted that a full report of the committee's proceedings has never appeared. The observatory is placed in a suitable and well-selected position in the parish of Charlton, near Woolwich; it has a convenient room built of wood, apart from the rest of the establishment, especially prepared for experiments in magnetism, and the examination of sea-compasses, to which it is devoted. The method of testing a compass is as follows:—Three pedestals, S, C, N, Fig. 142, are firmly fixed in the room, quite independent of the floor, in the line of the magnetic meridian. The south pedestal S carries a suspended magnet, which is observed by means of a transit telescope fixed on the centre pedestal C; on the pedestal N

* Johnson on the Deviation of the Compass, p. 41.

Fig. 142.



is placed the compass to be examined. The collimating magnet S consists of a hollow steel cylinder, ½ an inch in diameter, and about 6 inches in length, centrally suspended in an appropriate frame by a long silk fibre; a small lens is fixed in the north end of the cylinder, and there is an extremely fine scale of 160 divisions traversing it horizontally, and right across its centre. The transit on the central pillar C being duly adjusted and directed in the axis of the collimating magnet, its scale is observed to vibrate across fine filaments of spider's web, fixed perpendicularly in the tube of the telescope. The magnetic meridian being found by this means, the transit is turned over, and directed toward the north, upon a mark painted on a distant wall on a rising ground, called Cox Mount; this mark corresponds to the line of the collimating magnet on pedestal S; we thus transfer over, as it were, the line of the magnetic meridian as taken in the telescope upon the compass to be examined, and which is placed on the pedestal N. The needle and card being removed, the compass is so adjusted in position by appropriate apparatus on which it rests, as to bring the point of suspension of the needle in the line of the telescope, and so as to bisect it; this done the card is replaced, and its north pole is made also to coincide with the line of the telescope.

For the adjustment of the azimuth compasses there are a

set of graduated divisions painted on the distant wall, and the vertical line of the telescope conveyed through the window so as to cut these divisions; the prism is now adjusted for the zero point of the card, the hair-line of the sight-vane (150) being directed to the particular division on the wall, cut by the vertical line of the telescope.*

The pivots, caps, and gimbalds, and the metal of the compass-bowl, &c., are now carefully examined; also the magnetic power of the needles, which are tested by a standard magnetometer of deviation (134), so that errors liable to arise in any particular instrument are certain to be detected.

301. Attached to the Observatory is a museum containing a collection of sea-compasses of various kinds, and also other magnetic instruments. The following is a brief notice of some of the forms of mariner's compass found in the establishment:—

Compass by Mr. George, Master R.N.—The needle is a plane circular segment of thin steel plate, vertically placed above the card. The point of suspension is on a gimbald inside the kettle.

French Binnacle Compass.—A descending point rests on an agate plane, the position of which can be changed so as to renew the surface of suspension.

Compass by Preston.—Card and needle on a vertical axis, moveable between two centres; a method since adopted by Dent.

Compass by James Thomas—Has an axis of suspension, through a plate, as first employed by Preston, and since adopted by Captain Walker (286), Fig. 137.

Compass by Crowe, of Feversham.—The card is hollow, and of enamelled copper, placed in a fluid; it is buoyed up centrally against a point projecting downward from the glass cover. This was the original fluid compass (286).

Compass by Captain Kater—Has a double suspension, an upper suspension of silk fibre, so as to take the weight off the point beneath.

Old Prismatic Azimuth Land Compass.

Danish Azimuth, as employed in the Danish royal navy, has a telescope of observation, fixed across the azimuth circle. The gimbalds work on friction rollers.

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* Two of the plates of glass in the window are worked perfectly plain, so that no error may arise in this operation.

Azimuth Compass by Sydes and Davies.

Azimuth Compass by Blunt, of London.—A very old form.

Meridional Compass by Walker—Has a graduated concave arc over the card.

Compass by Wood, of Liverpool.—A cylindrical pointed magnet, of about 10 inches in length; is fitted to a system of graduated metallic circles, the whole set on a vertical axis.

Compass by Miller, of the Devonport Dockyard.—The needle is bent each way from the centre to about the angle of the dip, and is compounded of the flat and bar-edged needle.

Boats' Compasses of various Kinds.

Chinese Compass.—The needle is suspended on a point below its centre of gravity.

Binnacle Boat Compass by Preston.—A fluid compass. The fluid is one-third alcohol and two-thirds water.

Compass by Captain Phillips, R.N.—The needle is elliptical; the compass is on springs, and without gimbalds. It is poised on a central point, so as always to remain vertical.

Compass by Sir Edward Owen—Is hung on springs from the box, so as to yield to the concussion of guns.

Compass—Set in double gimbalds.

Spanish Compass.—The bowl is of wood; the card pasteboard.

Insulated Compass—Is set on glass legs.

Compass by Lieutenant Edye, R.N.—The needle is hung centrally by attraction at the pole of a vertical magnet, as occasionally practised in the chemical balance.

Experimental cards with various needles and pivots; about forty employed by the Committee.

Card in which the line of suspension may be adjusted to the axis of the gimbalds.

Patent Compass by Jennings.—The needle is within a hollow metal case, containing ferruginous matter.

Pope's Original Compass.—The needle is a flat bar, hung on a central axis, free of the card, so that it may take any dip.

The magnetic needle of the dipping instrument employed by Captain Cook.

Proposed Card by Captain Milne, R.N.—For meeting the deviations of local attraction. The card is figured for direction indicated in the ship.

Patent Card by Captain Sparkes, R.N., adjusted upon similar principles.

This observatory, so essential to the interests of the

navy, is under the direction of an intelligent naval officer, Captain Johnson, who is well versed in the science of magnetism, and is at the head of the compass department of the Admiralty.

302. The card of the mariner's compass, as we have before explained (144), is commonly estimated in terms of 32 points or rhumbs ;* it has, however, been found desirable for more refined purposes to estimate the angular deviation from the line of the magnetic meridian in degrees and minutes, taken in reference either to the north or south pole of the card; thus, instead of the rhumb N.E., we say N. 45° E.; instead of S.S.W., we say S. 22° 30′ W., and so on. The following, as a table of reference, may not be altogether superfluous.

Points.	Deg.	Points.	Deg.	Points.	Deg.	Points.	Deg.
	° ′		° ′		° ′		° ′
N.	0 0	E.	90	S.	0 0	W.	90
N. by E.	11 15	E. by S.	78 45	S. by W.	11 15	W. by N.	78 45
N.N.E.	22 30	E. S. E.	67 30	S.S.W.	22 30	W.N.W.	67 30
N.E. by N.	33 45	S.E. by E.	56 15	S.W. by S.	33 45	N.W. by W.	56 15
N.E.	45	S.E.	45	S.W.	45	N.W.	45
N.E. by E.	56 15	S.E. by S.	33 45	S.W. by W.	56 15	N.W. by N.	33 45
E.N.E.	67 30	S.S.E.	22 30	W.S.W.	67 30	N.N.W.	22 30
E. by N.	78 45	S. by E.	11 15	W. by S.	78 45	N. by W.	11 15
E.	90	South	0 0	W.	90	North	0 0

It is easy to observe here, from the north or south line, or 0° 0′, either in the upper or under line of the table, the degrees corresponding to any rhumb taken either east or west of the meridian. Thus we have for the rhumb E. by S. the expression S. 78° 45′ E.; for the rhumb W.N.W. we have the expression N. 67° 30′ W.

It has been further found convenient, in some especial instances, to take the angular measure from the north point only, all round the circle and in an east direction. Thus we should have for S.S.W. the expression N. 202° 30′, for N. by W. we have N. 348° 45′; it is further evident that

* The reader is requested to correct the following errors of the press in the table given p. 133, Parts I. and II. line 4, under E. read S.E. by E.; line 3, under S. read S.S.W.; line 4, under S. read S.W. by S.

we may represent in this way the position of any rhumb from either of the cardinal points N., E., S., W. taken as 0° 0′ in each quadrant. Thus we may represent E.N.E. as E. 22° 30′ northerly, taking E. as 0° 0′. The method, however represented in the table just given is that commonly employed.

303. *Local Attraction.*—By the term local attraction, as applied to a ship, we are to understand a certain disturbance of the compass under the influence of the general mass of the vessel considered magnetically, in virtue of the iron which it contains. The amount of disturbance will materially depend on the direction of the ship's head in respect to the needle, by which the ship's position as a magnet is varied (191). It is now but too certain that errors of the compass thus produced have led to afflicting cases of shipwreck. We owe the first intelligible notice of the local attraction of a ship to Mr. Wales, F.R.S., who accompanied Captain Cook as the astronomer of his expeditions in 1772-3-4. Mr. Wales observed, in the English Channel, differences in the azimuth compass of 19° to 25°, and afterward similar discrepancies all the way from England to the Cape. The greatest westerly deviations occurred when the ship's head was between N. and E. He was hence led to express his conviction, "that variations of the compass (149), observed with the ship's head in different positions, and even in different parts of the ship, will differ materially."* This was certainly the first notice of local attraction scientifically observed, and must not be confounded with notices of the common action of iron on the compass, mentioned by earlier navigators.†

304. In the year 1790, Mr. Downie, master of H.M.'s ship *Glory*, made an interesting report on this subject, in which he observes, "that in all latitudes, at any distance from the magnetic equator, the upper ends of iron bolts

* Wales's and Bayly's Observations on Cook's Voyages, p. 49.

† Sturm's Mariner's Magazine, published 1684. Dampier, 1680.

acquire an opposite polarity to that of the latitude,"—an observation in accordance with Marcel's experiment in 1772 (101); so that by induction they may attract or repel the north end of the needle, according as the ship is on the north or south side of the equator, thereby causing serious errors in the compass. Admiral Murray and Captain Penrose, whilst cruising off the Nap of Norway, observed a point difference in the direction of the compass when the ship's head was toward or turned from the land.*

In 1801 and 1802, this important inquiry received fresh impulse from Captain Flinders, who, in the course of his voyage of survey to New Holland, also observed differences in the magnetic needle, when no other cause was apparent than that of a difference of direction in the ship's head. When the ship's head was north or south, the needle was not influenced, but when east or west the difference in the direction of the compass was considerable. Captain Flinders conceives the magnetic force of the ship's iron to be concentrated into something like a focal point, nearly in the centre of the ship, having the polarity of the hemisphere in which the ship is placed.†

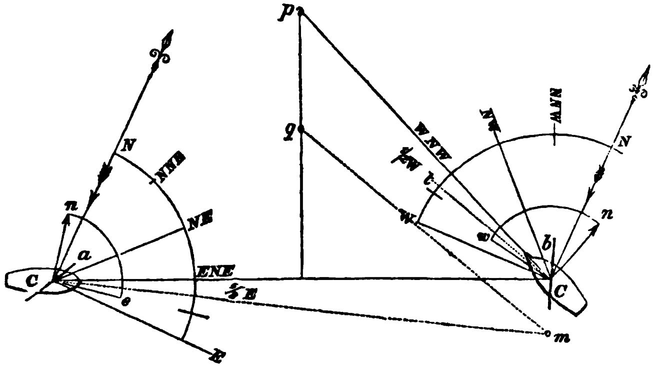
These important facts were, however, again lost sight of, until Mr. Bains, master R.N., published in 1817 a valuable little treatise on the variation of the compass; soon after which, in 1819, Professor Barlow undertook his capital course of experiments (234), with a view of computing and correcting this source of error. The question of local attraction since this period has received abundant and important verification from the labours of our celebrated navigators, Ross, Scoresby, Parry, Franklin, Fitzroy, King, and many others.

305. The errors liable to arise in the reckoning of a ship's course, may, from the local attraction of the ship, be of very serious amount. Let, for example, *a*, Fig. 143, be a vessel close-hauled upon the larboard tack, the wind being true

* Walker on Magnetism: London, 1794.

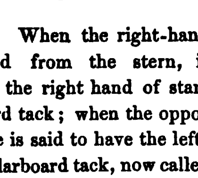
† Phil. Trans. for 1805.

Fig. 143.



north in the direction N C.* Then, since she sails within six points of the wind, her head will be true E.N.E., so that her course, without any other consideration, would be upon the line C c. Supposing, however, that with the ship's head in

Fig. 144.



* In all square sails set upon a cross-yard, pointed to the wind, as represented in the annexed Fig. 144, the rope *t* which confines the angle of the foot of the sail to windward is called the tack; and the rope *s*, which holds in the opposite angle to leeward, is called the sheet; these terms apply to either rope, according as they become placed on the one side or the other in respect of the wind. When the right-hand extremity *b* of the yard, as looking forward from the stern, is pointed to the wind, the vessel is said to have the right hand of starboard tacks on board, or to be on the starboard tack; when the opposite or left extremity *a* is pointed to the wind, she is said to have the left-hand or larboard tacks on board, or to be on the larboard tack, now called the port tack. The angle which the axial line of the ship makes with the direction of the wind, so that the yard, when trimmed to the wind, may cause the sail to remain full and without shake, and propel the ship, is reckoned in points of the compass, and thus a square-rigged vessel is said to be close-hauled when the axial line of the ship is brought within 6 points of the wind. Cutters with fore and aft sails may be made to sail within 4½ points of the wind, and even less.

this direction the local attraction causes the north pole N of the compass to deviate half a point west, and come into the line *n* C; then the true direction E.N.E. will read on the card as E.N.E. ½ E., for the E. point will then come up half a point, and the card will be canted into the position *n* C *e*.* In laying off the course, therefore, on a chart, for the ship's place, she would be reckoned as sailing on the line C M; and instead of having after a given time arrived at the point *c*, she would be set down as being, say at *m*. Suppose the vessel be now put on the opposite or starboard tack; then, being again trimmed within 6 points of the wind, her head would be really W.N.W. and she sails on the line *c p*. Suppose, however, that in this direction of the ship's head, the local attraction now turns the compass needle half a point the other way, that is, eastward; which it may; and the card is canted into position *n c w*, then the true direction W.N.W. would read on the card W.N.W. ½ W., since the west point would come up in a point;* and she would, in keeping the reckoning by compass, be taken as sailing in direction *c t;* which, laid off from the point *m*, where the ship was supposed to have been tacked, would make her supposed course *m q*; so that, after a second given period of time, the rate of sailing being observed, she would be supposed to have arrived at some point *q*, whereas she would actually be at some point much further northward, for example, at some point *p*. Now, if so great a difference may arise upon a comparatively small difference of half a point of the compass, how great must be the error when the deviation becomes four times that amount! It is therefore not at all surprising that very melancholy cases of shipwreck should have so frequently arisen, without any apparent neglect on the part of the officers of the ship. On the 26th of March, 1803, H.M.'s ship *Apollo*, with a convoy of seventy merchant vessels, sailed out of Cork, and at 3 A.M. on the 2nd of April following, the frigate and forty sail of the convoy found themselves on

* See (312) Fig. 147, p. 169, as applicable to this.

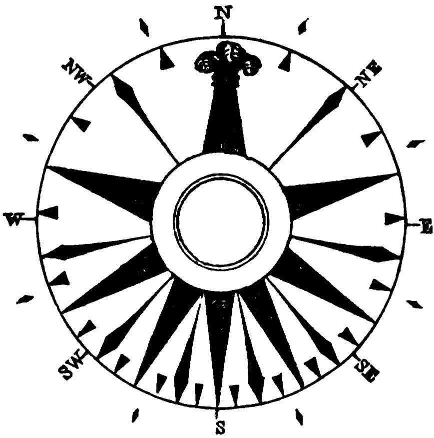
shore on the coast of Portugal, believing at the time they were 180 miles westward of it. The consequence was a most afflicting shipwreck. Another most remarkable instance is to be found in the wreck of H.M.'s frigate *Thetis*, which sailed from Rio the 4th of December, 1830, having on board a million of dollars. The ship's head being south-east by compass, they stood on until the next morning, thinking themselves clear of the land, and the wind coming free, they tacked, and set studding-sails. All at once, after a favourable run, they found the ship against the perpendicular cliff of Cape Frio, the ship running at nine knots. She went stem on to the rock in deep water; of course the bowsprit and all the masts were carried overboard, and the ship became a total wreck.

306. The greatest amount of disturbance hitherto observed in vessels built of wood, does not appear in certain positions to have far exceeded 20°, or about two points, still a very serious error in the course of a ship. In iron vessels, however, the disturbance may be so great as to render the compass next to useless. In the steam-ship *Shanghai*,* driven by a screw propeller, the deviation, with the ship's head south, as observed by Lilley, amounted in the binnacle compass to 171° 34′ W., being more than fifteen points.

It is very difficult to determine all the different arrangements in polarity incidental to the iron of a ship, especially in ships of war and iron-built ships, since every piece of iron in the ship may become magnetic by induction (191), the poles varying as the ship turns into new directions, and changing altogether with the latitude north or south of the equator. The disturbing effect on the compass also will be different under different angles of inclination, as was completely shown by Captain Walker, R.N., in a valuable set of experiments on the *Recruit*, an iron brig. We have hence a very intricate problem to solve. Fig. 145 represents the distortion of the compass in the *Indus*, that is to say, the

* Belonging to the Peninsular and Oriental Company.

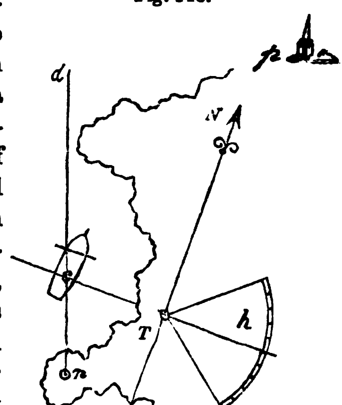
Fig. 145.



direction of the points requisite to a true course. In this figure the position of the regular points is indicated on the outer circle.

307. *Methods of determining the Effect of Local Attraction.*—To ascertain the disturbing effect of local attraction on the compass, the ship must be placed in smooth water in a slack tide, or in a basin, and must be so circumstanced as to admit of being gradually swung and secured in any direction on the 32 points of the compass by means of warps, mooring buoys, or anchors, as indicated in the annexed Fig. 146. The vessel being thus circumstanced, a very

Fig. 146.



distant object *p* is to be selected, and its bearing taken from a convenient station T, on shore, not liable to any magnetic disturbance. This bearing should be taken with a fine azimuth compass, to be employed as a standard compass of observation, and fixed in a given place on board the ship. Suppose the bearing of the distant object *p* at the station T were N. 35° E.: having determined this, we substitute for the compass a theodolite, or the azimuth circle, and adjust it so that the distant object shall read off exactly the same bearing, N. 35° E. The compass is now transferred to the ship, and set upon a firm pillar, in the midship line of the quarter-deck, say at the point C: an observer now takes the bearing of the pillar T on shore, at the same instant that an observer at T on shore takes the bearing of the pillar C on board, which is done by signal. If the ship does not influence the compass, then it is clear that these reverse bearings will coincide in the same line. Thus, if the pillar T bore due east from the ship, the pillar C would be due west from the shore. If this coincidence be not obtained, the difference is the local attraction of the ship. If, for example, whilst the pillar C on board bore due west from the shore, the pillar T bore from the ship east ½ north, that is E. 5° 37′ 30″ N., then the local attraction of the ship directed in the position in which she happened to be placed, would have been such as to have drawn the north pole of the needle 5° 37′ 30″ towards the east, and this would be the local attraction for that position of the ship. In this way, by bringing the ship's head successively upon each of the 32 rhumbs, and taking what are called cross bearings, we determine the local attraction or disturbance of the compass for each point of direction. This was the method first pursued by Professor Barlow, and it is perhaps as perfect as any.

308. The present method pursued in determining the local attraction of H.M.'s ships is somewhat different from this. The bearing of some very distant object *d*, Fig. 146, is first

determined by the standard compass C from the ship's deck, and for the ship's head directed upon each point of the compass; the compass is now taken on shore to some convenient spot *n*, and the same distant point *d* brought to coincide with the observer's eye and the pillar C, from which this bearing was taken on board, the ship being again swung successively upon the 32 points of the compass. If the ship had not disturbed the compass, the bearings should coincide in the line *n* C *d;* if not, the difference upon each point is the local attraction. If the object *d* be very distant, the bearings may be simply taken from the two stations C and *n*, without including the ship, and the difference set down as the local attraction without any sensible error.

309. Mr. R. Stebbing, of Southampton, has lately invented an extremely available and very valuable method of determining the local attraction of a ship, by which much labour is avoided, and time saved. A centre staff T, Fig. 146, with a flag on it, is set up on some chosen place on shore, and a segment *h* of the magnetic circle *h*, of about 100 feet radius, described from this point as a centre, long poles are then set up on this segment at each 5°, and other intermediate shorter poles on each single degree. The line T N of the magnetic meridian being carefully determined, the true bearing of the centre staff T, and its intersection with either of the poles of the segment *h*, are given; with a view to an easy distinction, the poles are either coloured differently, or carry small distinguishing flags. The observer on board at C has now only to take notice what degree the centre staff T cuts upon the circle *h* beyond it, and that is the true bearing; the difference as observed by the compass is the local attraction.

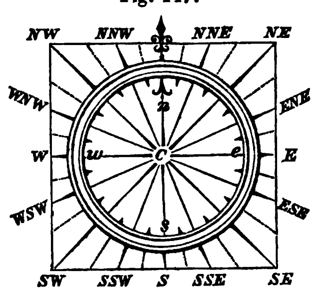
310. *Means of Correcting Local Attraction.*—The means of correcting the compass for local attraction, at present resorted to, are of the following kind:—1°. By determining a table of errors. 2°. By a compass card distorted so as to suit the particular ship (306). 3°. By the introduction of

new forces of disturbance, such as will either make known or compensate the disturbing force of the ship.

311. *Correction by a Table of Errors.*—This method of correction is evidently the first, as it is perhaps the safest, measure we can adopt, and is in all cases indispensable. The ship being swung in the way just described (307), the deviations corresponding to the direction of the ship's head are entered in columns of a table opposite each point of the compass, and the correction in steering a particular course applied. Suppose we required to make good a due E.N.E. course, and that with the ship's head in that direction, the table informs us that the north pole of the needle is drawn by the local attraction of the ship 5° 37′ toward the west, our course then must be E.N.E. ½ East nearly, for that would in fact be the direction shown by the card when the ship's head was in that direction (305).

312. In effecting a corrected course practically by a table of errors, it will be useful to possess what may be termed an indicator, by which the course to be steered by the standard compass, in order to make good any required true magnetic course, may be found mechanically by inspection.

Fig. 147.



This useful instrument may consist of a neat plane of wood Fig. 147, about ten inches square, covered with fine paper, and having the thirty-two rhumb-lines laid off on it, as given in the figure; a moveable compass-card *n e s w* is centrally placed on the board, so as to revolve round a central pin C. Now it is clear, that taking the fixed magnetic lines as the true lines, we may, by bringing any deviation for the north pole *n* of the card to either of these given fixed lines, immediately determine the course by the

standard compass, corresponding to the given course. Suppose, for example, we required to effect a N.E. course, and that in turning to our table of errors we found that with the ship's head in that direction there was an error of a point in easterly deviation of the compass. In such case place the north pole *n* of the card so as to correspond with the N. by E. fixed magnetic line, that is to say, move it eastward 11° 15′; this would then be the actual direction of the card of our standard compass in respect of the true magnetic lines, with the ship's head at N.E., and would hence bring the N.E. by N. point of the moveable card upon the fixed N.E. line, which shows, that to effect a true magnetic N.E. course, we must steer N.E. by N. by the standard compass.

We may, in a similar way, find the actual direction of the ship's head corresponding to a given course by the standard compass. Suppose, for example, the course by standard compass was N.N.W., and that with the ship's head in that direction, the needle deviated half a point West, set the moveable card to the deviation by turning the north pole *n* to the left hand, half a point, which will bring the N.N.W. line of the moveable card to N.N.W. ½ W. of the fixed chart, which will be the actual direction of the ship's head when steering N.N.W. by the standard compass. These are selected as illustrations of more complicated cases.

313. *Correction by Distorted Card.*—The ship being swung upon the different points of the compass, a card is marked off, such as on trial will correspond with the true magnetic direction of the ship's head, as shown (306) in Fig. 145, and by which the ship is to be steered. This method has been found very available and satisfactory, the objections are, that the irregular distances of the points of the compass confuse the helmsman, especially in steering ½ and ¼ points, and that it is almost impossible to take an accurate bearing with such a card. Captain Sparkes, however, who has lately obtained a patent for a card of this kind, has ingeniously applied a divided circle to

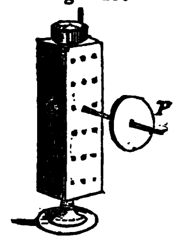
the verge of the compass, by which, when set to the course steered, any bearing may be taken. The idea of a corrected card appears to have been also suggested by Captain Milne, R.N., in an interesting paper on the subject of local attraction so long since as the year 1832.

314. *Correction by Compensating Disturbing Forces—Barlow's Plate.*—We are indebted to Professor Barlow for the first attempt ever made to correct the local attraction of a ship by a mass of iron placed in the vicinity of the compass, so as to introduce into the system a new disturbing force, which, acting at a given point, would produce the same effect on the needle as that of the iron of the vessel. In order to understand clearly this kind of correction, we must observe, that all the laws which Professor Barlow had determined in his researches concerning the operation of regular masses of iron on the needle (234), he found to obtain for irregular masses, whether as a system under the form of detached masses, as in a ship, or under any irregular form. In all cases a close approximation to the action of the system on the needle is arrived at, on the supposition that the force proceeds from two centres indefinitely near each other in the general centre of attraction of the mass, and that in iron bodies the magnetic force is confined to their surface.

From the first of these principles, confirmed by subsequent experiment, we may infer that the centre of action of all the iron of a ship, and the ideal line joining this centre with the centre of the needle, would be constant in all parts of the world; by the second we infer that a mere plate of iron may be so placed in this line as to produce an action on the needle equal to that of the ship; so that the disturbance produced by the plate being found experimentally, the disturbance due to the ship would be known. This principle was first employed by Professor Barlow in the following way:—The deviations of the compass being determined as before (307), the compass is taken on shore to a given

station T, Fig. 146, and there placed on a cubical box or case G, Fig. 148, moveable on a vertical axis into any azimuth (149). A circular double disc of iron P, composed of two thin plates of iron, fixed parallel to each other on an horizontal axis P, with intervening wood, and termed a compensator or correcting plate, is then applied at some point determinable by experiment at the side of the case, so as to project from it, and at some given distance in respect of the compass; the whole is now swung into various azimuths, and the disturbance of the plate P observed in each, as before done in respect of the ship; by a very few trials, such a position of the plate can be found as will cause it to produce precisely the same disturbances as those observed in the ship. The plate being capable of adjustment on the axis P as to distance horizontally, and on the case G as to height vertically, the position of the centre of the plate P is now carefully marked, and the compass replaced in the ship. If the plate be now applied as before, then, as is evident, the amount of disturbance will be twice as great; since the compass will not only deviate by the action of the ship, but also by the action of the plate. It is this double disturbance, however, which furnishes the required correction, because the new disturbance caused by the plate is exactly equal to the existing disturbance of the local attraction. Thus supposing the ship's head being N.E., the variation (149) as taken with the azimuth compass to be, without the plate, 22° 30′ West, and taken with the plate 29° 27′ West, then the difference 6° 57′ West is due to the plate; but this, as we have seen, is exactly equal to the iron of the ship. We must, therefore, to obtain the true variation, apply this correction to our first observation, which will make it 15° 33′ West; and to make a true N.E. course by the compass, we must steer N.E. $\frac{3}{4}$ E., that is N.E. 6° 57′ E.; the

Fig. 148.



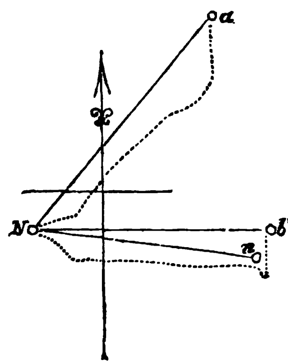
quantity by which the iron of the ship has drawn the north pole of the needle west, as shown by the plate.

315. *Balance of Errors by Barlow's Plate.*—Since the correcting plate P, Fig. 148, can double the disturbance when placed in a given position in respect of the compass, we may infer that, by changing its position, an opposite point may be found in which the plate would exactly balance the local attraction by a disturbance in an opposite direction; and such is found to be the case, or at least approximately. In applying the plate to the standard compass, either with this or the preceding view, the several bearings for each point (307) must be examined, when two opposite points will be commonly found in which the bearings nearly coincide, the mean of these must be taken as indicating a line of neutrality in the ship; the direction of the line must be noted, and in some point of this line the compensator must be ultimately fixed. To determine its exact position, Professor Barlow has drawn up a general table of local attractions comprising all possible limits of disturbance for every class of sailing ship in the royal navy built of wood, in which are found the limits of disturbance applicable to the given vessel; opposite these limits are two numbers, one representing the distance of the centre of the plate below the pivot of the needle, and the other its distance from the plumb-line or vertical passing through the pivot of the needle. At this depth and distance in the line of no attraction, and abaft the compass, the compensator will balance all the disturbance arising from the iron of the ship, so that on swinging the ship (307) the needle will be found without error.

316. This method of correcting the compass for local attraction, if not absolutely perfect, has proved eminently successful in practice; and why it has been discontinued in the royal navy, without further investigation, it is difficult to say: its great importance may be inferred from the annexed diagram, Fig. 149, which represents

the true and calculated courses of H.M.'s ship *Griper*, between the 25th and 26th May, 1823, as laid off from the ship's log. In this diagram, N denotes the ship's place at noon by astronomical observation, 25th May; and *n*, the place of the ship at noon, also by astronomical observation on the next day, 26th May. According to her calculated place by the uncorrected compass, she would have been found at *a*, but by the compensated compass at *b*, very near her true place, making a difference of 35 miles of latitude, sufficient to have shipwrecked the vessel (305).

Fig. 149.



317. *Correction by Magnets.*—Some important practical observations having in 1835 been made by Captain Johnson on an iron steam-ship, the *Garry Owen*, from which it appeared that the ship operated upon a compass-needle placed outside the ship, after the manner of a permanent magnet, the Astronomer Royal, Professor Airy, was led, in July, 1838, to undertake an extensive experimental and analytical investigation of the whole subject, with a view to discover such general laws of the magnetic disturbance in iron ships as would enable him to correct the local attraction. This fine physical and mathematical inquiry will be found in the Transactions of the Royal Society for 1839. It would be impossible, however, within the limits of so unpretending a work as this, to do full justice to Professor Airy's capital paper; we can only hope, therefore, to treat it in such a general way as may apply to the question before us.

Whatever be the number or direction of the magnetic bodies in a ship, the effects on the compass may be resolved into three forces,—one directed to the ship's head, one toward the starboard side, and one directed downward verti-

cally. If we represent the effects which depend solely on the arrangement of the ship's iron by two constants P and N (that is to say, forces which do not change, and which may here be determined, and which become the multipliers or coefficients of certain unknown quantities) the one, P, being a coefficient upon which the force transverse to the keel depends, and the other, N, a coefficient upon which an induced force, similar to that of permanent magnetism, depends; and if the arrangement of the iron be symmetrical with respect to the keel, and the compass placed in the middle of the breadth, then taking the deviation of the north end of the needle in an east direction, it may be represented by $P \times \sin. 2A + N \times \text{tang. } \delta \times \sin. A$; in which A is the azimuth of the ship's head reckoned eastward, and $\delta =$ the dip. Should the general mass of the iron be at the same height as the compass, or should different masses of equal magnitudes constituting the iron of the ship have equal elevations and depressions in opposite azimuths, then the constant N will vanish. The constant P will vanish when the general mass of the iron is below the compass, or when equal masses are 90° distant, as seen from the compass.

In the application of Barlow's plate, Professor Airy conceives that it only neutralizes the term dependent on N, but not that dependent on P. To obtain a perfect compensation, we must place another plate at the elevation of the compass in an azimuth of 90°, either to the right or the left of the first plate as commonly applied; in this case P will be also compensated.

Besides these coefficients P and N, we have a third also to consider as depending on the absolute diminution of the directive force in a north and south line, and which we may call M; this term is greatest when the iron mass is above or below the compass, and least when at the level of the compass.

The forces to be considered, according to the results of his inquiry, estimated by their action on the north pole of the needle, are four; viz. the force of terrestrial magnetism

towards the north = unity; permanent magnetism in direction of the ship's head; permanent magnetism to starboard side; induced magnetism to the starboard side. This last force may be resolved into induced magnetism toward the north, represented by $-\text{M} + \text{P} \times \cos. \text{A}$; and induced magnetism toward the east, represented by $\text{P} \times \sin. 2\,\text{A}$.* By far the most considerable of the disturbing forces are those dependent on permanent magnetism: these were not found to change in whatever position the ship was swung. The induced forces appear to be comparatively small.

The horizontal intensity in the ship directed in the line of the compass, as also the terrestrial intensity on shore taken = 1, is determined by the needle of oscillation (254); the ship being swung into different positions.

Professor Airy having brought the various forces of disturbance under the dominion of theory and calculation, proceeds to destroy them by the introduction of other and opposite disturbing forces.

The longitudinal and transverse forces may be corrected by the action of a single magnet placed at a given distance below the compass, with its poles so directed as to draw the north end of the needle toward the ship's head and starboard side; or otherwise by two distinct magnets, which is much more convenient. The induced force toward the east, or $\text{P} \times \sin. 2\,\text{A}$, may be corrected by placing a mass of iron on a level with the compass, either on the starboard or port side: with these correctors duly applied, the compass was found free of disturbance.

The only chance of error in this correction is the uncertain value of the induced force N, and its variable character in different latitudes; there is, however, every reason to suppose that it is extremely small, and may, in

* The induced force we have called N is omitted here, being intricately combined with the permanent magnetism in the direction of the ship's head; the force M also, not producing any effect in an east and west direction, is omitted.

certain dispositions of the iron of the ship, vanish altogether, so that the correction for one latitude may, without sensible error, be used in all latitudes.

The correction of the compass then, in iron ships, becomes reduced to the compensation of force of permanent magnetism toward the head; of permanent magnetism toward the starboard side; and the term depending on P, the effect of which in an easterly direction is represented by $P \times \sin. 2A$; omitting N as being small, and M because it does not disturb the compass.

318. The practical method of effecting these corrections is to swing the ship as before upon the cardinal points, then, by means of two magnets and a mass of iron, to correct the disturbances. The magnets are placed by trial upon some point in one of two lines carefully determined, one parallel to the keel, the other at right angles to the keel; these lines are either traced on the deck, or on the ceiling below the deck timbers. If the ship's head be north or south, and the transverse magnet be shifted by trial until the compass points correctly, it will be certain then that the force to or from the starboard side is compensated. Similarly, if the ship be swung east or west, the longitudinal magnet is shifted until the compass again points correctly; the force to or from the head is now compensated. To correct the force represented by $P \times \sin. 2A$, the ship must be swung into the intermediate points N.E., N.W., &c., and the compass made to point correctly by means of a mass of iron; an iron chain, for example, placed by trial, either on the port or starboard side.

As it is requisite in this operation to correct the compass simultaneously with the observation of the deviation, the very ingenious method pursued by Mr. Stebbing, of Southampton (309), is of the greatest value in this case.

Some vessels are more easily managed than others. The compasses in one vessel may require a single magnet only; others require two, with the addition of a box of iron chain.

The *Ripon* has two magnets and chain for each compass. The *Pottinger* had a single magnet only, aided by a chain. The *Ariel's* compass was corrected by one magnet only, without any auxiliary aid.*

319. Many objections have been raised, as may be easily imagined, to these methods of compensating the forces, disturbing the compass by the introduction of other disturbing forces, such as the liability of the relations of the magnetic forces to change with change of place and with time; the influence of changes of temperature on the correcting magnets, as also the liability of the magnets themselves to vary in power, such objections are of course inseparable from this kind of investigation, and we can only determine their validity by experience. So far as experience extends, it cannot be denied, but that the compass as corrected in iron ships by Professor Airy's method, has, upon the whole, acted remarkably well. The commanders of the iron ships *Sultan*, *Pottinger*, *Harbinger*, and many other large steam-ships, report most favourably of the efficiency of their compasses thus corrected. The latter vessel, corrected by Lilley, has been in a southern latitude, without finding any material change in the balance of the forces. We cannot certainly consider the question to be so definitely determined as to render all further observation unnecessary; it is very important, as stated by Professor Airy, to subject the vessel from time to time to further examination, and carefully note all the changes which are liable to occur. There is little doubt but that compasses corrected by permanent magnets are affected by time and by geographical position, but still not to such an extent as is likely to lead to any very sensible error, or an error which may not be provided against. Some very interesting remarks by Mr. J. R. Stebbing, on this important question, will be found in the "Artizan" for August, 1850. Mr. Stebbing conceives that "the practical difficulty of correct-

* "Artizan" for August, 1850.

ing compasses for iron ships is overcome, and that such ships are as safely navigable as ships built of wood." Messrs. Lilley also, who have corrected the compasses of more than fifty iron ships by permanent magnets, and by a method of observation of their own not generally known, also report confidently on the efficiency and safety of the principle deduced by the Astronomer Royal.

Ships, however, destined for long voyages, should still depend materially on a table of errors (311), registered for a standard compass, whatever other method of correction of the compass be resorted to:—corrected cards (313) are decidedly useful, especially in iron ships, and may be employed with advantage in conjunction with other means to determine the true magnetic course.

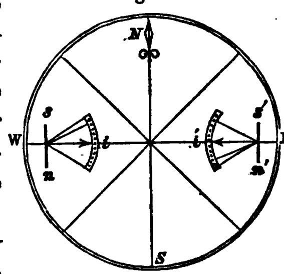
320. The following are a few important facts as deduced by Mr. Stebbing, from his experience of iron ships:—

1. A compass may be very true on one or several points, and greatly disturbed on others. 2. The errors in one ship are no guide to the errors of another. 3. The errors are least toward the middle of the vessel. 4. Every iron ship is a magnet in itself: some have the north pole aft, and some the south. The magnetic axis is frequently determined diagonally through the ship. 5. There are in all iron ships two points, either opposite or nearly so, at which there is no error; there are other two points where the error is the greatest. An error will not sometimes alter 3 degrees in a range of 5 points, and then change 30 degrees in the next 5 points. 6. The deviation is always an accumulating error or the reverse: it runs, 1, 3, 7, 12, 17, 26, 30, 32, 33, 31, 28, 24, 20, 17, 13, 9, 6, 3, 0; but never, for example, thus—3, 7, 4, 10, 8, &c.

321. We must not dismiss this most important subject without a brief notice of an ingenious compass by Mr. St. John, of Buffalo, United States of America, and which was rewarded with a medal at the late Great Exhibition: the object of the arrangement is to indicate the amount of

local attraction, and the deviation of the compass actually present at any moment. This invention is shown in Fig. 150, in which N E S W represent the suspended card and needle: *n s*, *n′ s′*, are two short slender needles, delicately set up on vertical axes and attached to the compass-card, one on each side of the centre of the great needle; and on the east and west line, these small needles, termed satellites, carry fine indexes *i*, *i′*, made of reed, centrally fixed to them and at right angles to their direction, so as to indicate on graduated arcs *i*, *i′*, any deflection to which they are subject. Supposing the compass to be in the true magnetic meridian, the three needles will be parallel, but the small needles will stand with their poles *n s*, *n′ s′*, reverse to the poles S, N, of the large needle (14, 31). If under these circumstances the compass-needle N S deviate from the true meridian, then the position of the small needles *n s*, *n′ s′*, will vary from parallelism, and indicate on their respective arcs *i*, *i′*, the amount of deflection to which the compass is subject; at least this is the conclusion arrived at by the inventor. The notion is extremely ingenious, and the contrivance as a mechanical arrangement very elegant: it requires, however, much further investigation before the principle can be considered as being perfectly available.

Fig. 150.



CONCLUSION.

322. We have now gone through, in as comprehensive a way as the limits of our work will permit, all the great leading facts of ordinary magnetism, theoretically and practically considered, and have at the same time entered upon

the several important physical questions to which they have reference; we have now merely to advert in conclusion to some of the more recent applications of this branch of science in furthering the progress of civilization, or in contributing to the wants of mankind.

323. The next great practical application of magnetism, after the mariners' compass, is the auxiliary means it has afforded in the construction of the electrical telegraph, and without which that wonderful contrivance could never have been made so perfect as it now is. For although the electrical current is the great element by which the transmission of thought is effected between persons separated by almost any amount of distance, yet it is by the varying motions and positions of the magnetic needle, ever obedient to the wire affected by the current action (40), that we owe the interpretation of the ideas or thoughts, concealed and conveyed as it were through the wire. Having already explained in our volume on electricity* the general telegraphic agency of the electrical current, and the means afforded to its transmission through wires continued through various points of space, we shall limit ourselves here to a notice of the more immediate part of this wonderful contrivance so far as it depends on common magnets, the various motions of which constitute, as it were, the language of the instrument.

324. It will be immediately seen by reference to the phenomena of electrical wires and magnetic needles, already explained (40, 41, 46), that one or more needles, finely set upon an axis, either vertically or horizontally, may be caused to assume various positions, and may be deflected any number of times successively, either to the right hand or to the left, and almost at any point of distance from the source of power, provided the means of communication of the current be afforded; and thus we have an interpretation of events at

* Rudimentary Electricity, second edition, p. 191.

hand, according to any preconcerted code of signals. We have likewise seen (53) that by making or breaking contact with a voltaic circle, a piece of soft iron may be vigorously attracted toward the poles of an electric magnet, or be again easily separated from it. We have here then a further source of motive power at a distance, by which machinery may be set in motion, alarms sounded by means of bells, and other audible signals effected. When a single needle is employed, the code is termed the single-needle code. The arrangement consists of a magnetic needle, or set of needles, *a*, Fig. 152, enclosed within a galvanometer coil (46), and set on an axis; the axis projects horizontally, and carries a vertical index-needle, *b*, in front of a silvered brass dial; the alphabet is engraved on the dial, right and left of the index-needle, as in the annexed Fig. 151.

Fig. 151.

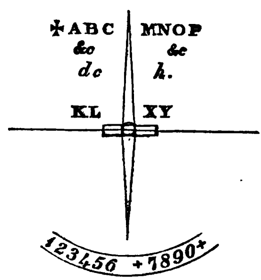


Fig. 152 represents the position of the galvanometer coil and needle *a* behind the plate, with the axis and needle *b* in front of the plate. The two needles are placed with poles reverse to each other (29), and both are more or less acted on by the coil. In order to give the system a tendency to the vertical position, a slight preponderance in weight is given to the lower extremities of the needles. The extent of deflection is limited by pins fixed on the dial.

Fig. 152.

325. The letters are indicated by successive deflections, or beats of the needle, communicated by the current from a distance to the galvanometer arrangement behind the plate and in given directions; thus the letter L is indicated by four successive deflections, right, left, right, left. The last beat is always the end of the word, and is a left-hand beat.

326. In the double-needle code two galvanometers are employed, and two index-needles placed parallel to each other; the double-needle code gives, of course, increased facility, as admitting of a greater number of combinations. In this arrangement two galvanometers (46), with their respective needles, stand side by side; one is called the left needle, the other the right needle. Now we may either deflect the right needle or the left, or both at one time, causing their upper or under points to converge to the same letter, and furnishing signals which may easily correspond with a given code; thus, the upper half of the left-hand needle twice deflected to the left may be A, three times B, once to the right and once to the left C, and so on. In order to spell the word HEN, for example, a first beat is made with the right needle for H, then a second with the left needle for E, now a third beat with the right needle signifying N; finally, a fourth beat with left needle, corresponding to the symbol ✠, signifying the termination of the word. In order to render these movements of the needles effectual, there are two handles below the dial by which the connection with the voltaic battery (40) can be, by means of a particular mechanism, rapidly made, so as to cause the current to flow in any direction (41). In the double-needle arrangement everything is, of course, doubled.

327. Professor Wheatstone, to whom we are mainly indebted for the needle apparatus, also contrived a method of signalizing the letters themselves. This is effected by a circular dial, or disc, set on a central axis, and on which the alphabet is engraved, as also the numerals. The circumference of this plate, taken edgewise, has a succession of insulating and conducting intervals, so that in turning it round we effect or break contact with the battery, by means of a spring pressing against the surface. Any series of letters we choose to make appear at a given opening in a case covering the dial will be repeated at a distance by a similar dial. This is effected by the temporary magnetizing of soft

iron, in making and breaking contact with the battery (53) as we turn the disc round to a particular letter. By this, as in the motion of the alarm-bell, a motive force is obtained at a distance, the mechanism operated on being so arranged as to turn by electro-magnetic action, any required letter of the distant dial to the opening in its corresponding case. Thus, if we signalize at any station the letters F I R E, in succession, then the same will successively appear upon the opening of the dial at a distant station, say of 100 miles. This species of telegraph has been termed the mechanical telegraph, in opposition to the former, which has been termed the needle-telegraph, and which is that commonly employed in this country.

328. Although to an observer the manipulation in working the telegraph dials may appear complex and perfectly incomprehensible, and the delivery of a message at the rate of eighteen words per minute from a hundred miles distant quite marvellous, yet the practice of the operations is very soon acquired by the clerks engaged in this department of our railways; indeed, after great experience, the manipulator can work with a blank dial; and the particular clerk employed at the distant station to transmit the message, may be actually known by his characteristic deflections of the needles right or left. One is firm in his signals, another sharp and rapid; one patient, another hasty.*

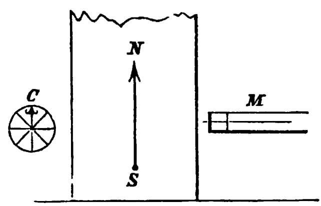
329. The application of magnetic influence in determining distance through otherwise impermeable matter, or the thickness of solid rock or other substance, may be considered as another valuable application of ordinary magnetism, especially in mining operations. We are indebted to the Rev. Dr. Scoresby for this method of measuring distance.

It is evident that since the deviations of a delicate needle, by the influence of a magnet placed in the line of its

* Walker on Telegraphic Manipulation.

centre at right angles to the meridian (134), may be taken as a measure of the force of the magnet; so, conversely, the same deviations, under similar conditions of direction, must correspond with equality of distance; that is to say, supposing the intervening matter to be permeable or transparent to magnetism. If, therefore, we determine for a given magnet and needle a table of deviations corresponding with certain distances between the centre of the needle and magnetic pole when placed in a given position, we may thereby determine the distance at which the magnet is operating through solid matter, by observing the deviation produced.

Fig. 153.



Let, for example, C N M S be a mass of solid rock, S N the direction of magnetic meridian, and that the walls of the mass lie in that direction; let C be a delicate compass, finely divided, and placed on one side of the rock, and M a magnet placed perpendicular to its centre on the other; the compass-needle will then be deflected a certain number of degrees; from which the distance may be found either by the table, or by bringing the magnet round to the side of the compass, and finding experimentally the distance at which the same amount of deviation will be produced. If the intervening rock should lie oblique to the meridian in direction S N, and the compass-needle become oblique to the walls, we must then deflect it by the influence of an auxiliary magnet, so that it may stand parallel to the walls of the rock, and then proceed as before. By a careful preparation of the apparatus, Dr. Scoresby has succeeded in measuring distances of 126 feet to within a very small fractional amount.*

330. Ordinary magnetism is employed for the separation

* Edin. New Phil. Journal, April, 1832.

and collection of particles of iron, mixed with other finely-divided matter, by means of permanent magnets, as also to the most important and humane purpose of catching up, in a similar way, the destructive dust of steel, which, in the grinding of needles, is liable to find its way into the eyes and lungs of the workmen, thereby producing diseases of a serious character, more especially of the lungs.

331. Common magnetism is in this way made available in a machine for separating from impurities disintegrated particles of certain rich ores of iron found in Canada, and which average from 60 to 70 per cent. of pure iron. These ores, by exposure to the wearing action of the atmosphere, freely break up into small grains; they are then stamped and dressed, after which the magnet is used to act on the disintegrated particles, and thus separate the iron from its gangue.

THE END.

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